Part IV

Applications

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WearCare – Usability of intelligent materials in workwear

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19.1 Introduction

Conditions in many industrial jobs are challenging regarding protective clothing. Traditionally, workwear fabrics are durable and may be water, oil or chemical repellent as well as flame retardant, but may not be especially comfortable. Temperature regulation, flexible ventilation or size and shape regulation has been possible only recently with so-called intelligent textile materials. In the healthcare sector the comfort of patients as well as medical personnel could be improved with intelligent textile applications, such as textile embedded sensors, which may be used for monitoring body functions like temperature and heartbeat.

Wearable technology was the first step towards intelligent textiles. By attaching electronic devices to pieces of textile or clothing electronics became wearable. This, however, was not very comfortable to the user, and several challenges remained unsolved, such as washability, cables that remained visible and heavy power sources. During the past four to five years interactive textiles or so-called intelligent textiles have emerged. Many of them are still at a very early stage of development, but new solutions are being developed continuously. This was well demonstrated by the third Avantex[1] symposium and exhibition held in Frankfurt in June 2005.

Intelligent textile materials are becoming more practical and their interactivity is being enhanced making them a real alternative for workwear and healthcare apparel. The extensive R&D efforts being carried out in this area will no doubt result in numerous breakthrough inventions and applications in the near future.

19.2 Objectives

'WearCare' was a joint project between the Department of Textiles & Fashion

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[1] www.avantex.messefrankfurt.com

Design of the Faculty of Art & Design at the University of Lapland[2] and the Institute of Fibre Materials Science at the Tampere University of Technology[3] between 2000 and 2003. As at the start-up of the project the intelligent textile concept was still rather new and not yet presented to the market, the objective of the project was to evaluate the usefulness of intelligent textile materials in general and particularly in the health sector and in the high-temperature working environment.

Secondly, the aim of the project was to analyse and define how intelligent garment properties could be illustrated and presented by means of 3D design techniques, as such properties are often invisible and difficult to demonstrate. Defining the usability of futuristic and conceptual designs is difficult due to lack of prototypes. The third objective of the project was to develop visual methods for presenting to potential users the ideas and properties of intelligent garments that may be made in the future.

19.3 Methodology

The project partners included the two earlier mentioned universities, textile producer Finlayson Forssa Oy,[4] a workwear manufacturer, Image Wear Oy[5] and Nokia Research Centre.[6] The University of Lapland concentrated on design and usability testing and the Tampere University of Technology on intelligent textile materials. Conceptual design leaned heavily on market and user research, which was carried out in two hospitals for the healthcare products and in a steel mill for the protective clothing products. Based on product designs, an extensive search for suitable interactive textile materials as well as communication devices was carried out.

The consumer-needs model FAE (functional, aesthetic, expressive) by Lamb and Kallal was chosen to be the testing method. Functionality in the model refers to the fit of the garment, the mobility it allows, comfort, protection and ease of dressing and undressing. Aesthetic properties refer to the design and art elements, such as line, pattern, colour and texture. Expressiveness means the communicative or symbolic characteristics of a garment. Computer animation was also used for visualisation of the product concepts. The animations built around hospital and high-temperature work environments demonstrated various intelligent properties, such as communications and transmitting of alarm and distress signals.

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[2] www.ulapland.fi

[3] www.tut.fi

[4] www.finlaysonforssa.fi

[5] www.imagewear.fi

[6] http://www.nokia.com/nokia/0,50249,00.html

19.4 Textile materials

There are specific standards for textile materials to be used in the healthcare sector and especially in patients' clothing, by which material composition, weaving structure, washing ability and colour fastness are defined. Polyester and cotton are the most commonly used materials. It would be possible to use phase change materials as well as colour change materials for improving user comfort and for signalling, but their use would be restricted by standards. Textile embedded sensors and electronics are therefore more feasible applications.

The requirements for protective clothing in high-temperature environments are defined by two standards, EN 340,[7] which outlines the general requirements and EN 531,[8] which presents the requirements for protective clothing against molten metal splatter. DuPont's aramid fibres (Nomex[9] and Kevlar[10]), glass fibre, silica fibres, and BASF's Basofil[11] fibre are among others fibres that are very heat resistant and flame retardant. In areas where radiating heat stress is high, it is necessary to use heat-reflective aluminium-based materials for protecting both the user and any embedded electronics. Such materials have traditionally been very rigid and uncomfortable. BASF has, however, developed two new approaches. One is a warp knit-based material with aluminium coating, which is flexible and more comfortable. The other one is a woven fabric made by using Basofil yarns and Nomex yarns as weft and Kevlar yarns as warp. Basofil-fibre has a high LOI value (Limited Oxygen Index[12]) and does not transfer heat well. The fibre is used in woven, knitted and non-woven structures-with various application area as shown in Table 19.1.

Phase change materials are suitable as underwear or as a jacket worn under the protective clothing, especially during winter in cold climates when the temperature may vary extensively. Heat radiation may produce very high temperatures while in other parts of the plant the temperature is below zero. Three-dimensional fabrics, for example, Spacetec by Heathcoat,[13] may be

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[7] http://www.idec.gr/ppe/en/EN340.htm

[8] http://www.idec.gr/ppe/en/en531.htm

[9] http://www.dupont.com/nomex/

[10] http://www.dupont.com/kevlar/

[11] http://www.basofil.com/

[12] The Limiting Oxygen Index (LOI) indicates the relative flammability of polymeric materials. Index 'LOI' is defined as the minimum concentration of oxygen in an oxygen–nitrogen mixture, required for downward burning of a vertical test object. The higher the LOI value the more flame retardant the fabric is. The LOI test is widely used for determining the relative flammability of rubbers, textiles, paper, coatings and other materials. Standards: BS 2782 (Part 1, Method 141), ASTM D2863 and ISO 4589-2.

[13] www.heathcoat.co.uk

Table 19.1 Basofil fabrics

Composition	Weight (g/m^2)	Application
100% Basofil or 20–60% Basofil and 40–80% aramid	370–600	Firefighters' suit when coated with aluminium, protective clothing against splashing molten metal, protective industrial gloves, protective aprons, protection in welding
60% Basofil and 40% cotton	220–300	Industrial protective clothing, knitted protective gloves
60% Basofil and 40% flame retarded viscose	140–240	Linings, upholstery
40–70% Basofil and 30–60% para-aramid	220–290	Protective clothing, against splashing molten metal when coated with aluminium, firefighter's coverall
20–60% Basofil and 40–80% meta-aramid	150–220	Industrial protective clothing, automobile racing, knitted hoods for firefighters

used for knee areas and material composition can be chosen according to each purpose. Thermochromic materials for high-temperature colour change were not commercially available during the project.

19.5 Electronics

Embedding electronics in clothing is challenging. Beside washing and ironing problems electronics may not always function properly especially in demanding working conditions. Usability surveys have also shown that consumers do not appreciate solutions that are uncomfortable with bulky devices and visible cables. Instead of wearable technology future innovations and product applications focus on integrating electronics fully into textile structures. Nanotechnology may be one way of solving such problems, and with ultra-light and strong nano-tubes textile structures can be made conductive. During the project such solutions were, however, not commercially available.

Communications, music, localisation and monitoring of biosignals are normally the properties associated with textile-integrated electronic systems. Several prototypes have been developed and some have even been launched commercially, although real breakthroughs remain still to be seen. An example is the musical jacket developed by Philips and Levi's which has a communications system and an MP3 player.[14] In this jacket, as in all wearable

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[14] www.media.mit.edu/hyperins/levis

computer products, all electronics are removable and have to be removed if the jacket is washed.

Tele-medicine is an interesting area offering a wide range of possible applications that combine textile-based sensors, wireless communication and monitoring of patients' biosignals from a distance. Applications may range from pure monitoring of the patient to disease prevention and rehabilitation.

Batteries, the traditional power source, fit poorly in line with the objectives of making intelligent garments comfortable. Other solutions must be found. Current research and development focuses on tiny fuel cells, textile-integrated batteries and exploitation of excess body heat. A transducer, which converts body heat to electricity, would be a perfect solution.

Various types of natural-user interfaces and connections have been developed for intelligent textile products, ranging from press-buttons to Velcro tapes. Tapes, bindings and zippers can be used for integrating cables into the garment. Pressure-sensitive textiles are used for keyboards, and sensors may be laminated or embroidered on fabrics. Metal and carbon yarns and conductive polymers can be integrated into the knit or woven fabric and used for signal transfer. An example is DuPont's Aracon fibre, which has been applied to heart-rate-monitoring sensors. One of the problems with conductive yarns is how to produce a yarn with an even level of resistance. Thüringen Institute[15] is currently developing a conductive cellulose-based filament by using the lyocell[16] process. Their aim is to produce a fibre with a wide scale of resistance controlled by the relative quantity of carbon (35–100%). With a high proportion of carbon in the fibre resistance increases up to a point, which makes it possible to use a fabrics made from this fibre as heating elements. Gorix[17] is an example of commercially available carbon-based fabrics that can be used for heating elements, but it cannot be applied for all purposes as it still requires a powerful energy source.

Encapsulation of electronic devices is necessary in order to make them washable and to isolate them from high thermal radiation. Thermoplastic encapsulation techniques have been developed against heat, shocks, water and chemicals and it can be applied to microchips, connectors, microsensors, switches and keyboards. This kind of protection is necessary in workwear for high-temperature environments. Encapsulation must, however, not block sound waves, for example, when microphones or loudspeakers are attached to the garment.

Optical fibres are useful for illumination and signal transfer when attached to textile materials. Fibre optic sensors are able to measure temperature, pressure, gases and smells and they can function like nerves when attached

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[15] www.titk.de

[16] www.lyocell.net

[17] www.gorix.com

to textile structures. Such sensors are of very light weight and flexible, they need no electric insulation and do not cause electromagnetic interference. Light from an LED source can be transferred through optical fibres to areas where light is not sufficient. This light could also be used for alarm signals. France Telecom presented a fibre optic display prototype at the Avantex exhibition in 2002. It was a rather robust display attached to a backpack woven of optical fibres and controlled by mobile phone. This was an invention produced by France Telecom's Studio Créatif within their special research programme called 'Communicating Clothes'.[18] Further development of this idea has resulted in a bluetooth-operated LED screen, which displays text, drawings and animations transferred by a multimedia messaging service.

Project WearCare focused on communications, monitoring of body functions and temperature regulation. The aim was to find rather than develop suitable textile-based solutions for making such functions possible. There are already suitable applications that could be used and are commercially available but ideal solutions were not found. Furthermore, extensive prototype testing in actual working environments (steel mill and hospital) should be undertaken in order to ensure that the solutions function properly and maintain their durability for a longer period of time. This, however, was to be done in the second phase of the project.

19.6 Usability testing

Standards EN 531 and EN 340 define the requirements for textile materials to be used for workwear in high-temperature conditions. Several other standards define the requirements for testing electronics parts. Testing temperature varies usually between 125 °C and 150 °C. The most efficient method for testing the behaviour of intelligent materials are physiology tests carried out with real persons or simulated with a thermal sweating manikin.

Current test methods are not very suitable for testing the thermoregulating properties of phase change materials, as the traditional testing method is based on a static quantity of air in the clothing. Intelligent materials are dynamic thermoregulators and they interact with skin and environmental temperature changes. Differential scanning calorimetry (DSC)[19] is used for measuring the thermocapacity of a garment or the enthalpy of a single microcapsule of the fibre containing PCM capsules. This method is normally used for measuring the melting and crystallising temperatures and heat absorbing and releasing potential of different materials. Thermogravimetric analysis (TGA) is a method for estimating thermal resistance of a microcapsule,

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[18] http://www.studio-creatif.com/Vet/Vet02Prototypes05Fr.htm

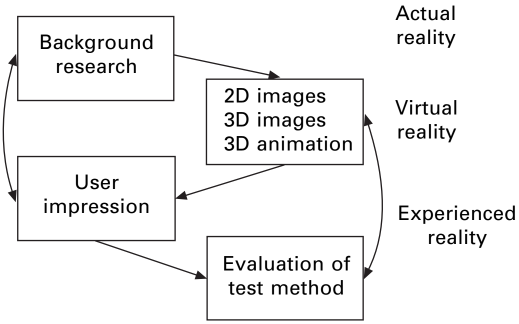
[19] www.msm.cam.ac.uk/phase-trans/2002/Thermal2.pdf

as the capsule must endure the process temperatures in fibre production, spinning, weaving and fabric finishing.

At temperatures above the fusion point of carbon hydride, steam pressure rises inside the capsule causing weight loss. Normally there are two weight loss points: at 100 °C water starts to vaporise and at 280–310 °C carbon hydride escapes as capsule walls collapse. In order to prevent considerable weight loss, the temperature at which the capsule walls collapse must be clearly higher than the textile process temperatures. Doctor Doug Hittle of Colorado State University has developed a method called TRF for testing the performance of phase change materials. The equipment and method simulates physiology tests with human beings and measures the temperature-regulating ability of fabrics.

Usability testing methods applied within the project consisted of background study, virtual reality produced by 2D and 3D images and animation, analysis of users' impressions and finally evaluation of the test method. The empirical testing method is described in Fig. 19.1. Two collections of patients' clothing and three collections of high-temperature workwear were designed and visual images as well as animations were produced. Prototypes were, however, not produced, as the objective was to be able to evaluate which properties are preferred by users before launching expensive prototype production. Furthermore, this testing method allows for futuristic ideas to be tested before actual technology for producing them is available. Both patients' clothing and workwear contained non-visible intelligent solutions, such as tele-monitoring and communications.

Background research was carried out by interviewing patients and personnel in two hospitals and workers in a steel mill. Information collected through these interviews was used as a guideline for designing the collections. Both 2D and 3D images of each garment in the collections were produced. The animation demonstrated how the intelligent functions were performed and what help and assistance they would provide to the user. Altogether 13 patients, 5 nurses and 10 steel mill workers carried out the test. The test



19.1 Empirical testing methodology.

person was first given background information and told about the project objectives. Then he or she watched the multimedia animation, was shown the product images, and was interviewed according to a pre-set questionnaire. According to the Lamb and Kallal's conceptual model the usability evaluation was based on functional, aesthetic and expressive properties. Functional properties are further defined by comfort, ease of dressing and undressing, protection, fit and mobility.

The patients regarded modifiability of clothing and colours as most important issues regarding comfort, followed by pocket applications and protective properties. Materials, however, were not regarded very important in terms of comfort. Two kinds of intelligent applications were attached to the patient's clothing, an interface that could be used, for example, for calling a nurse and for adjusting the bed angle and maternity pants for monitoring body functions of a fetus with pregnant women. The patients rated calling for nurse and adjusting bed angle as most important functions in patients' clothing. The hospital personnel regarded calling for nurse and monitoring of biosignals as most important features. Monitoring of fetus biosignals was also rated important. For details see Table 19.2. In addition to the intelligent properties patients and hospital personnel both regarded expressive and aesthetic aspects of clothing important in supporting patients' self-esteem and mental well-being.

High-temperature protective clothing collections contained such intelligent solutions as hands-free communications with textile-embedded microphones and loudspeakers operated with a pull-aid user interface, heating panels for back, textile-embedded wrist lights and heat radiation reflecting body shield. Heating panels for back, hands-free communication system, pull-aid user interface and hearing protectors made of textile fabrics were rated as most important intelligent properties by steel mill workers as shown in Table 19.3.

Table 19.2 Importance of intelligent properties in hospital clothing

n = 13 patients, 5 maternity patients, 5 personnel	Patients	Personnel
Calling for nurse	69%	80%
Dinner menu selection	23%	20%
Clothing selection	31%	20%
Control of massaging socks	15%	20%
Adjusting bed angle	54%	20%
Monitoring of biosignals	38%	60%
Music selection	15%	20%
Maternity pants for monitoring fetus biosignals	40%	40%

Table 19.3 Importance of intelligent properties in high temperature work wear

n = 10 steel mill workers	Steel mill workers
Heating panels for back	100%
Hands-free communication system	83%
Pull-aid user interface	80%
Hearing protection made of textile fabric	80%
Speciality knee protection	77%
Heat radiation reflecting body shield	50%
Wrist lights	45%

19.7 Conclusions

Setting standards and developing testing methods is a long process, and existing standards or test methods may not be suitable for testing totally new functional textiles, as was the case in this project with phase change materials. Researcher creativity may be the only solution for deciding how such materials should be tested until proper standards and test methods are developed. As well as textile functions, the functionality of electronics, communications, signal monitoring and transfer must also be tested. When electronics are embedded to textile structures flexible encapsulation against moisture and heat, as with high-temperature workwear, becomes necessary. Such properties may not be required from conventional electronic devices and therefore traditional testing methods may not be suitable.

The number of intelligent textile innovations and their applications in clothing will no doubt increase in the future. At the moment numerous research institutes as well as industrial companies are busy developing such innovations and applications. Intelligent textile innovation projects are very cross-scientific requiring skills and knowhow not only regarding textiles, but often electronics, signal transfer, communications and medicine. The aim is to develop something new, which we have no prior experience of and whose usability and functionality may be questionable. Therefore, concept planning with usability testing is a rational first step before producing prototypes or bringing the product to the market.

One of the main objectives of project WearCare was to investigate how useful 3D modelling and animations are in usability testing, specifically when we need to find out the impressions and opinion of the potential user. Such systems, when successful, would enable the research team to analyse their product concepts and ideas at a very early stage and would make it possible to eliminate errors and handicaps that might cause the product to be unusable. The results of WearCare clearly demonstrated that 3D modelling and animations can be successfully used for early-stage usability testing. Patients, hospital personnel and steel-mill workers were able to identify which features were desirable and which in their opinion were not so important. The results of the usability test proved to be very valuable and they produced hands-on guidelines for further research and development.

19.8 Bibliography

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Intelligent textiles for medical and monitoring applications

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20.1 Introduction

Healthcare is a key market for the textile industry. In the year 2000, over 1.5 million tons of medical and hygienic textile materials, with a value of 5.4 billion dollars, were consumed worldwide. It is estimated that this figure will increase in volume by 4.5% per annum, so that by 2010 it will have reached 2.4 million tons, with a market value of 8.2 billion dollars (David Rigby Associates, 2002). Thus, the healthcare and medical sector offers the greatest opportunities for developing the most sophisticated high value textiles for niche applications (Czajka, 2005) and is one of the most important areas to foster growth. Within the textile industry there is ever-increasing competition from manufacturers worldwide that brings the need to find developed markets for specialised products, in a sector that is changing from traditional production methods to advanced technology. This consideration is especially important for countries with high labour costs such as those of western countries.

Intelligent textiles combine various technologies from different fields, mainly from the traditional textile industry and from research in technologically advanced smart materials. The incorporation of these technologies into textiles and vice versa will open new opportunities for intelligent textiles in medicine and medical monitoring. Among the possible applications of intelligent textiles, wearable systems and ambient intelligence are two of the most important. Wearable systems integrate information and communication technologies in garments. Integration into clothes and textiles is one of its major objectives. Ambient intelligence is a way of making interfaces between humans and computers disappear (Gaggioli *et al.* 2003). Ambient intelligence implies an intelligent environment, in which computers disappear or become transparent. Integration of an interface in clothing is one of the latest trends in this line of research. One example of this is the development by TU Berlin of the technology for embedding active devices (chips) in the inner layers of flex laminate (Vanfleteren and Lutz-Günter, 2005). BAN (body area network), PAN (personal area network), smart clothes and other devices placed in the body that will be able to detect patients' vital signs and retransmit them to sorting nodes, in real time (Gaggioli *et al.* 2003) are some examples of the potential for this technology in medical applications. Within ambient intelligence, intelligent textiles can be considered as a transparent interface incorporated in clothes, or as sensors for recording the user's activities. Both approaches are highly suitable for medical and monitoring applications.

The incorporation of interfaces and sensors into clothes is a highly attractive option for medical and monitoring applications as it facilitates the automatic sensorisation of the activity. If sensors are included in the garments, wearing the garments equals to sensorisation. This is superior to other approaches to e-health. Also, wearable medical devices are often rejected by the user as they highlight the existence of pathologies or medical problems. If the devices are integrated in clothing this problem disappears. The advantage of intelligent textiles for medical applications is due to two reasons: they are in contact with the skin, and they follow the user's movements and therefore make possible the sensorisation of physiological and biomechanical parameters. However, there are two drawbacks that have to be dealt with: the high impedance of skin contact for recording physiological signals and the draping movements of garments (Martin *et al.,* 2004), which mean that the follow-up of movements is not precise. This consideration should lead to new techniques for analysis and treatment of the signals provided by intelligent textiles. New approaches and techniques are necessary instead of the established algorithms and procedures.

These approaches will lead to new concepts in health, with a better quality of life for patients and lower social costs, changing the model from a system in which citizens have to go to a centre where they receive medical attention (hospital-centred health systems), to a system in which the attention is individualised and delivered to the user wherever he may be (citizen-centred health) (Lymberis and Olson, 2003). This chapter focuses on the applicability of intelligent textiles to medical and monitoring uses from a practical perspective. The importance of intelligent textiles in medical and monitoring applications is described in section 20.2. Section 20.3 analyses the potential applications of medical textiles grouped into diagnosis/complementary explorations, secondary prevention and healing/medical treatment. In section 20.4 the existing intelligent textiles technologies applied to monitoring and medical treatment are described. Finally, in section 20.5 future trends and applications are considered.

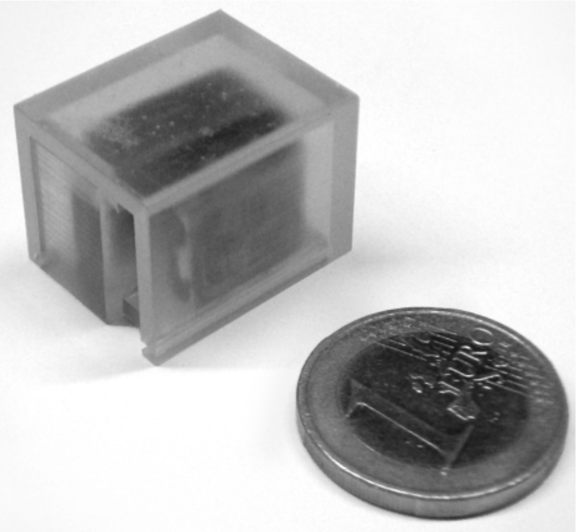
20.2 Importance of intelligent textiles for healthcare

Major social changes, progress in science and technology and increased medical knowledge are driving the evolution of healthcare and health delivery

(Lymberis and Olsson, 2003). Present-day society is undergoing changes such as ageing of the population, further integration of people with disabilities and an increase in chronic diseases. The control of these diseases is critical, as seven major diseases (heart disease, cancer, diabetes, arthritis, chronic bronchitis, influenza and asthma) accounted for 80% of deaths in the US in 1990. For many of these health problems, early systematic intervention would be highly beneficial (Park and Jayaraman, 2003). However, this intervention has to be carried out keeping in mind the direct annual medical cost, which leads to the search for alternative solutions. The healthcare industry must meet the challenge of balancing cost containment with maintenance of desired patients' outcomes (Park and Jayaraman, 2003). In this context, wearable electronics and intelligent textiles may become key elements in ambient intelligence (Catrysse *et al.,* 2004). In fact, the possibilities of unobtrusive long-term monitoring from intelligent textiles could benefit, among others, patients with spinal cord injuries, the cognitively impaired, elderly people living at home and infants at risk of Sudden Infant Death Syndrome (Van der Loos *et al.,* 2001; Gibbs and Asada, 2005; Korhonen *et al.*, 2003). Although the costs are low and there is a high degree of integration with the user, which makes them very attractive, there are some aspects that should be pointed out regarding these potential treatments.

20.2.1 Levels of integration of the devices in textiles

There is no one single 'intelligent textile' or 'wearable device' able to gather and process all the signals generated by the human body. Each application needs to acquire different physical parameters or to act on different parts of the body. Also, the devices can be integrated to different degrees in textiles, depending on the cost, desired complexity and application. At the first level, solutions can adapt to clothes (i.e. a pocket to hold a mobile phone). At the next level, electronics and/or microsystems can be integrated into clothes (Fig. 20.1) or into textiles with connectable modules (e.g. with textile conductors). The third level of integration consists of embedding active structures in the textile fibres (e.g. woven displays). There is still another level; active fibres are the micro-electronic building blocks, such as transistors or diodes (Lee and Subramanian, 2005). However, substantial developments of flex technologies (Strese *et al.*, 2005) are still needed to convert these applications into commercial products. At this level, textronics appears as a new interdisciplinary branch of science with synergic connections between textile science, electronics and computer science. The objective of textronics is to obtain multifunctional, smart textile products of complex inert structure but with uniform functional features (Gniotek and Krucinska, 2004).



20.1 Microelectronics triaxial gyroscope. (Instituto de Automática Industrial.)

20.2.2 User requirements for intelligent textiles

The use of intelligent textiles as wearable devices (sensors or actuators) must satisfy a series of user requirements in order to guarantee results and the appropriate response in use (Korhonen *et al.*, 2003):

- Reliability, robustness, and durability. The environments in which the sensors need to operate vary, and the users are nonspecialists not necessarily aware of the technical limits of usage.
- Look/unobtrusiveness. Intelligent textiles must be integrated into the everyday life of the users. Hence, their appearance should either fit in with the individual's preferences or they should 'disappear', i.e., be as unobtrusive as possible. As textiles are used by everybody in their daily lives, the integration of intelligent textiles will not present serious problems.
- Communication. The sensors and measurement devices should be capable of transferring their information to some central data storage, preferably by means of a fully automatic system, or at least so easily that it does not pose a burden to the user.
- Zero maintenance and fault recovery. An important issue in the case of health monitoring is self-calibration and drifting avoidance, i.e., finding ways to guarantee that the sensor performance does not deteriorate over time. Calibration and accuracy are two issues that are obviously fundamental (Teller, 2004).
- Customization. Sizing of the wearable sensorised systems and

confidentiality of the obtained data are two aspects in regard to the user that must be considered in the development of intelligent textiles applications.

20.3 Potential applications of intelligent textiles

The range of intelligent textiles applications in medicine is fairly wide, ranging from clinical monitoring, in which a continuous flow of data is produced during long periods of time, to a drug-administering treatment. Doctors need tools that permit them to improve the performance of treatments and subsequently increase the quality of life of their patients. Several models can be employed to classify intelligent textiles in health and monitoring applications but, if the patient's welfare is taken as the criterion, there are two approaches that can be considered as adequate. The first classification involves the participation of the patient in interaction with the system embedded in the textile. According to this criterion, medical applications of intelligent textiles could be classified into disease management and remote monitoring. The second classification criterion considers the role that intelligent textiles may play in each clinical phase; diagnosis, prevention or treatment. This last classification will be used in the present section to describe in detail the potential application of intelligent textiles.

According to the first classification criterion, medical applications of intelligent textiles can be carried out in two different modes:

Mode 1: In disease management the individual is actively participating in the management process. An example of this type of application is a diabetic subject who may be monitoring blood glucose values, storing these results in a database, and receiving feedback. This will be used in evaluating the success of a pharmacological treatment or a diet to improve the blood glucose balance or the regime of activity, sport, etc. In this model it is the individual who is actively willing to receive feedback regarding his wellness or disease status and to participate in his own care (Korhonen *et al.*, 2003). The role of the physician is to support and advise the individual in his daily activities affecting the management of the disease. The capability of the system integrated in the textile to communicate in a comprehensible manner with the patient is a fundamental factor in maintaining motivation for continuing use of technical devices.

Mode 2: Remote monitoring is often related to independent living. In this model, the main (and often only) consumer of the measurement data is the caregiver, and the individual is not interested in or capable of interpreting the measurements (Korhonen *et al.*, 2003). The health status of an elderly subject living alone might be remotely monitored to detect possible deterioration in the subject's health status, or to detect sudden problems such as falls or health hazards (Perry *et al.*, 2004). Telemonitoring ECG (Bonato, 2003) could be useful in patients with unstable cardiac diseases in certain phases. If the patient complains of heart-related symptoms, by using the device, he/she may send the ECG to the care centre for review and judgement of whether immediate help is needed.

The ease and automation of use of the technical devices is strongly emphasised as the users may have limited technical skills, compromised capabilities to attach wearable sensors on a daily basis, and/or reluctance to accept any new technical device to be worn on their body. Besides, since their independence may be entirely due to the monitoring system, the subject will be highly motivated to accept the possible inconvenience caused by using the system. Integration is also a key factor for user acceptance. Most of the reasons for rejecting current approaches are social exclusion for wearing visible devices that may be a sign of disease or a health problem. If the applications can be part of the clothes or are an in-depth integration with user garments, acceptance (and therefore commercial success) will increase.

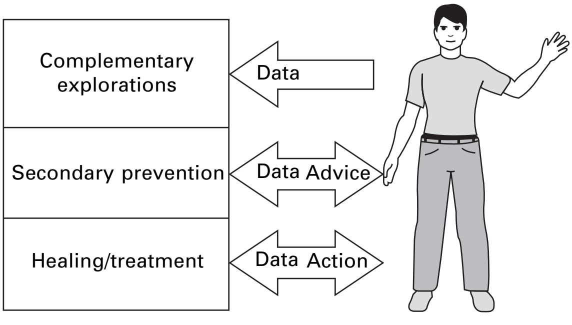
According to the second criterion, potential applications can be classified as follows (Fig. 20.2):

Diagnosis/complementary explorations: Monitoring and recording of signals (i.e. Holter monitors, body temperature, sweating, etc.).

Secondary prevention: Detecting associated risks and communication of physical changes (i.e. biofeedback) to avoid health problems.

Healing/medical treatment: Acting on an existing problem and modulating the response (i.e. intelligent orthosis).

Inside these general groups, there exist particular cases of especial interest due to the prevalence of the disease or the seriousness of the illness. In the following subsections the main potential applications in complementary exploration, prevention and treatment are described.



20.2 Classification of medical application of intelligent textiles according to the clinical phase.

20.3.1 Diagnosis/complementary explorations

Clinical monitoring of physiologic signals, such as electrocardiogram or blood pressure, provides only a brief window on the physiology of the patient. The interaction of variability in heart rate and blood pressure supplies information about higher regulatory systems, such as the systemic arterial baroreceptors. Insight into such higher-order control systems permits even greater understanding of disease pathogenesis and, potentially, disease therapy. However, the brief periods of clinical monitoring limit the potential of these data, mainly because of three major shortcomings (Binkey *et al.,* 2003):

1. They are likely to fail sampling rare events that may be of profound diagnostic, prognostic or therapeutic importance.
2. They fail to measure physiological responses during normal periods of activity, rest and sleep, which are more realistic indicators of the health of the patient.
3. Brief periods of monitoring cannot capture the circadian variation in physiological signals that appear to reflect the progression of disease.

To overcome these problems, devices that readily supply this information in an integrated fashion over a complete 24-hour interval in an outpatient setting would be the solution. However, even though there are several current research projects that are trying to solve this problem, a complete application is still not available (Binkey *et al.*, 2003).

In this section, the main monitoring applications in which intelligent textiles may play a fundamental role are described. Heart rate and blood pressure are basic in medical diagnosis and their control will reduce significantly the number of serious health problems. Patterns of movement and EEG are used in diagnosis of neurological diseases and as an input to decide treatment. Obtaining these data in a non-invasive manner will increase the health status of the patients and subsequently their quality of life, and will permit them to adapt to the treatment in real time.

Heart rate

A classical application in which ambulatory measurements are required is in the exploration of cardiovascular diseases. It is known that variability in heart rate over a 24-hour period is an important indicator of disease evolution and progression. A lack of diurnal heart rate variability is characteristic of patients with congestive heart failure (CHF) and cardiomyopathy and is likely to be a result of the profound abnormalities in autonomic function that characterise these patients (Binkey *et al.*, 2003). Patients with CHF have in common an imbalance of the autonomic nervous system, which may contribute to the progression of circulatory failure and influence survival. The sustained imbalance of the autonomic tone over a 24-hour period may promote the progression of circulatory failure and predispose these patients to malignant ventricular arrhythmias and sudden cardiac death (Panina *et al.,* 1995). Similar observations have been made in patients with ischemic cardiomyopathy (Binkey *et al.*, 2003). Diurnal variations in heart rate variability may indicate specific times of day that a patient may be more responsive to a given therapeutic intervention and may be a helpful tool for indicating the optimal timing of effective drug administration.

For all the above reasons, ambulatory systems for ECG monitoring (Bartels and Harder, 1992) (Panina *et al.,* 1995) have been part of the routine evaluation of cardiovascular patients for almost three decades (i.e. Holter monitors). However, these systems are not suitable when monitoring has to be accomplished over periods of several weeks or months, as in a number of clinical applications (Bonato, 2003) and their poor signal quality limits the accuracy of arrhythmia classification algorithms to fully monitor and manage rhythm disorders. Although impressive advances have been made in recent years in the field of ECG, there are still some problems that remain unsolved (Lobodzinski and Kuzminska, 1998) (Catrysse *et al.*, 2004).

The capacity of intelligent textiles to non-invasively detect physiological signals makes them the ideal candidate to solve these problems. Also, as they have the capacity to implement the equivalent of servo-controlled administration of therapy, they may also greatly improve the efficacy of treatment for cardiovascular disease (Binkey *et al.*, 2003).

Blood pressure

Patients with hypertension who fail to experience a drop in blood pressure during nocturnal intervals have been found to have a greater risk for events such as stroke and greater end-organ damage, such as renal dysfunction (Binkey *et al.,* 2003) (Engin *et al.*, 2005). Persistent rises in arterial pressure imply disturbance in the complex and multifactorial cardiovascular control mechanisms. In this context, neurohumoral disturbances could play a special role, in view of the fact that they have demonstrated that elevated sympathetic drive seems essential in hypertensive patients. Parameters obtained by spectral analysis of heart rate variability (HRV) might furnish useful information on autonomic normal and abnormal nervous system regulation (Pagani and Lucini, 2001).

Patterns of movement

Neurological disorders such as Parkinson's disease (PD) or hemiparetic stroke severely affect motor functions. PD is the most common disorder of movement affecting at least three per cent of the population over the age of 65. The characteristic motor features are development of a rest tremor, bradykinesia, rigidity and impairment of postural balance.

Several lines of research provide preliminary evidence that motor function in humans can be enhanced after a stroke through exercise and perhaps with medication. Dopamine therapies are often successful for some time in alleviating abnormal movements, but most patients eventually develop motor complications as a result of the treatment.

A reliable quantitative tool for evaluating motor complications in PD patients would be valuable both for routine clinical care of patients as well as for trials of new therapies. In routine care, it would be very useful to obtain information on a patient's motor pattern during the course of several days and then relate this to the timing and dose of medications (Binkey *et al.*, 2003).

EEG

Ambulatory electroencephalography (AEEG) monitoring allows prolonged EEG recording in the home setting. Its ability to record continuously for up to 72 hours increases the chance of recording an ictal event or interictal epileptiform discharges (Waterhouse, 2001) and is a useful tool in the study of sleep disorders, etc.

20.3.2 Secondary prevention

Secondary prevention aims at the avoidance of health problems in people at risk. The scope of secondary prevention is the analysis of clinical risks and its communication to the user or the carer to avoid adverse consequences. The possibility of inclusion of sensors and advice devices into the garments of the users should lead to a broad new range of applications in this field.

Detecting clinical risks and communicating physical changes to the patient or the carer may save children's lives in the prevention of sudden infant death syndrome (SIDS) (Park *et al.*, 1999), reduce deaths of elderly people caused by falls, increase the quality of life of people with dementia or Alzheimer's and detect critical situations when monitoring patients in post-operative recovery.

Sudden infant death syndrome

SIDS is the sudden death of an infant under one year of age that remains unexplained after a thorough case investigation. In the last 20 years the incidence of SIDS has been steadily diminishing (since 1983, the rate of SIDS has fallen by over 50%), but there are still about 2500 deaths per year in the US, and thousands more throughout the world. One of the methods suggested for preventing SIDS is a home monitoring system (American SIDS Institute, 2005). Online monitoring of heart and breath rates of infants and their integration into children's clothing are an area of research interest (Hertleer *et al.*, 2002).

Prevention of falls

Other critical cases in which the life of the patient may depend on the transmission of information to the carer are falls in elderly people and potentially dangerous situations due to agitation in people suffering from dementia. From 1992 through 1995, 147 million injury-related visits were made to emergency departments in the US. Falls were the leading cause of external injury, accounting for 24% of these visits. Emergency department visits related to falls are more common in children less than five years of age and adults 65 years of age and older. Compared with children, elderly persons who fall are ten times more likely to be hospitalised and eight times more likely to die as the result of a fall. Trauma is the fifth leading cause of death in persons more than 65 years of age, and falls are responsible for 70% of accidental deaths in persons 75 years of age and older (Fuller, 2000).

There are several biomechanical parameters that can be used as options for the assessment of the risk of falling. Inertial sensors (accelerometers or gyroscopes) are good candidates because of their light weight and size. A change in the pattern of movements of the trunk of a user at risk of falling can activate an alarm system to advise the user to take additional safety measures to avoid falling (i.e. when sitting or leaning on a wall).

Detection of states of agitation

According to the United Nations, the population of the developed countries was 1143 million in 1990, with 143 million of these being aged 65 or over. Applying the prevalence rates for various age groups given above, we arrive at an estimate of 7.4 million persons with dementia (Prince and Jorn, 1999). Given that Alzheimer's disease generally makes up the majority of cases in the developed countries, more than half of these people would have Alzheimer's disease (i.e at least 3.7 million people). The agitation that can occur in association with dementia greatly complicates patient care, poses a risk to the patient's health and safety, and significantly increases the burden for families and carers. Alarm systems and medical bracelets are solutions nowadays used to control patients. But the information provided by these systems does not include the health or agitation level of the patient. As harmful or violent behaviour towards self or others is possible in some patients, they can easily break the bracelet or any other wearable device. Integration of healthcare systems into textiles is the only feasible solution for controlling the situation and health status of this group of patients. There are many possible strategies for the analysis of a state of agitation; heart rate, breath rate, EEG or galvanic skin conductivity. Inertial sensors can also be useful as changes in the length of stride can be indicative of a state of agitation.

Biofeedback

Biofeedback is a therapeutic technique in which an individual learns to consciously control involuntary responses such as heart rate, brain waves, or muscle contractions. Information about a normally unconscious physiological process is relayed back to the patient as a visual, auditory, or tactile signal. These responses are electronically monitored and noted through beeps, graphs, or on a computer screen, which are seen and heard by the participant (Newman, 2003).

Biofeedback has been playing a significant role in the prevention of health problems such as urinary incontinence (UI) in women through the monitoring of pelvic floor muscles (PFM) contraction during therapeutic exercises with surface EMG (Tries and Eisman, 1995). Other applications of biofeedback are the control of attention deficit hyperactivity disorders (ADHD) in children through monitoring with digital polygraphs, or the prevention of repetitive strain injuries in workplaces using surface EMG (Pepper and Gibney, 2000). Biofeedback can be greatly improved through the integration of electronic monitoring systems in garments, to allow feedback monitoring when and where the measurements are required; in the workplace for injury prevention, at home for daily activities, etc.

Patients undergoing a physical therapy regime in post-operative recovery need to find out if they are doing their exercises correctly and if their range of movement is increasing. Intelligent textiles integrated into clothing could be a tool to inform patients and carers about the recovery process (Gould, 2003). In daily life, injured people may need information about the potential risk of an action (i.e. lifting a weight or reaching a limit position). Devices like the Intelligent Knee Sleeve, provide audible feedback with respect to changes in knee flexion angle during movements (Munro *et al.*, 2003) in order to prevent an excessive stress that may worsen the problem. The generalisation of this application to other parts of the body could be a useful tool for traumatologists and physiatrists.

20.3.3 Healing/medical treatment

Ambulatory medical treatments are, in most cases, based on drugs for different purposes or, in orthopaedic surgery patients, may require an orthosis.

Delivery of drugs

Medical treatments based on the administration of drugs may be a problem in some patients (i.e. in children) due to the concentration of the dosage and, in the case of dependent people (i.e. people with dementia), since a carer may be necessary to supply the proper dose of the drug at the right time. In other cases, such as in external treatments (i.e. ointments), some patients may have difficulties in reaching certain parts of the body or the dose may be inadequate. For these cases, materials that release substances open up a huge number of applications as drug supply systems in intelligent textiles (Van Langenhove and Hertleer, 2004).

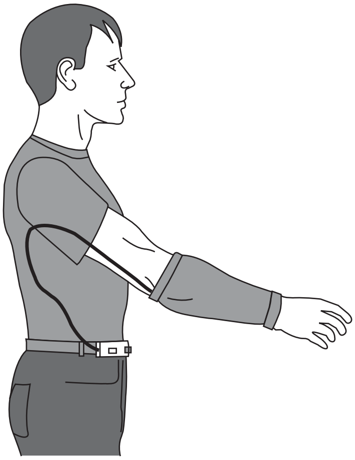
Wearable orthoses

The development of wearable ambulatory devices (orthoses) that mechanically suppress upper-limb tremor while preserving, as far as possible, natural movement, could vastly increase the quality of life of patients. Tremor can be a significant problem to sufferers of essential tremor, multiple sclerosis, Parkinson's disease and other neurological problems resulting in movement disorders, when engaged in the activities of daily living, requiring particular dexterity such as eating, dressing and writing (Manto *et al.*, 2003). The categories of tremor to be addressed are those resulting from progressive neurological disorders, such as Parkinson's disease and multiple sclerosis as well as tremor resulting from cerebellar trauma, and atypical essential tremor. The DRIFTS project has allowed the development of a wearable device that filters out undesirable movements, allowing the patient to carry out his daily activities (Manto *et al.*, 2003; Belda-Lois *et al.*, 2005; Loureiro *et al.*, 2005; Rocon *et al.*, 2005). However, the DRIFTS results are only a first approach to improving quality of life, as its weight and invasivity are still a problem. The use of intelligent textiles as force actuators may significantly improve the device, increasing comfort and wearability (Fig. 20.3).

Although wearable solutions are being developed, there are still many integration problems to be solved in order to transform the prototypes into really usable products. Most of the wearability problems may be solved by means of intelligent textiles used as sensors and actuators, reducing the weight and volume of the device. Thus, intelligent textiles and garments that provide an appropriate degree of comfort have a high market potential (Bartels, 2005).

20.4 From medical needs to technological solutions

In section 20.3 a series of medical needs were described, ranging from sensors for EMG to drug delivery systems and alarm systems for dependent



20.3 Prototype of DRIFTS orthosis. (DRIFTS QKL6-CT-2002-00536).

people. All these needs have something in common; the patient's independence and quality of life will be dramatically increased if it is possible to integrate the systems into a textile. A comfortable shirt or suit or a sheet for patients that have to remain in bed would be a less invasive solution and would alleviate the user's sensation of being ill and controlled, besides the clinical advantages.

All components of interactive electromechanical systems (sensors, actuators, electronics for data processing and communication and power sources) can be made from polymeric materials, to be woven directly into textile or printed or applied onto fabrics (Engin *et al.*, 2005). In this section, the existing intelligent textiles used as sensors, actuators and in communication are described. Some of them are existing commercial products and others are still under development.

Integrating the aforementioned components into textiles is not an easy task, and several problems have to be solved. Some questions, such as getting textile-shaped energy supply systems (Seyam, 2003; Powerpaper, 2005) or washability (Kallmayer *et al.*, 2005; Martin *et al.*, 2004) are common to all the applications, but others are specific to a certain case. Before designing a system based on intelligent textiles with a definite purpose, design criteria based on studies of existing wearable electronic and medical devices similar to the new product should be carried out (Teller, 2004). However, one thing is fundamental to guarantee the success of the intelligent textile application; user needs (Buhler, 2000) must be considered from the initial phases of the development, otherwise the final product will be useless.

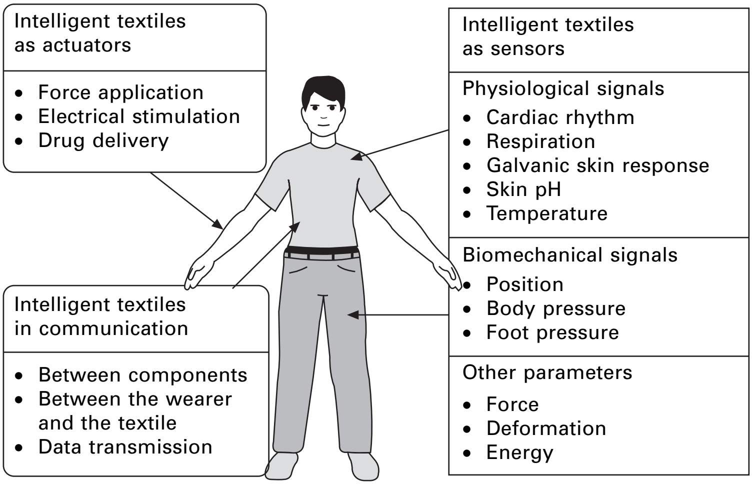
20.4.1 Intelligent textiles as sensors

To fully qualify as a smart textile, a sensor and actuator have to be present in the textile structure (Engin *et al.*, 2005), but nowadays most of the experimental and commercial intelligent textiles act as 'sensors + communicators' or 'sensors + data storage'. Various body signals (see Fig. 20.4) can be acquired by means of the specific properties of smart materials capable of being embedded into textile structures. In fact, there already exist, both as prototypes and also as commercial products, several applications of intelligent textiles that are being used to obtain data from the subject's physical response.

In this subsection, sensoring applications have been classified, according to the type of acquired data, into physiological signals, biomechanical signals and other parameters. However, the most interesting applications are achieved by combining several measurement techniques (Van der Loos *et al.*, 2001) to obtain a more complete subject diagnosis that overcomes the disadvantages of the classical methods (guardians and clinical polysomography).

Physiological signals

Physiological signals may supply critical information to doctors and carers about the health of the patient. In fact, the proper identification of patterns or occasional phenomena in these data could avoid a high percentage of deaths. Heart rhythm, breath rhythm, temperature, galvanic skin response and pH sensors are described in the following paragraphs.



20.4 Intelligent textiles in clinical and monitoring applications.

Heart rhythm

Several initiatives have been developed in order to integrate cardiac rhythm sensors in textiles. The 'smart shirt' wearable motherboard, which can be used in persons who have known disorders, permits a constant monitoring of their physical condition by medical personnel in a non-invasive manner (Park and Jarayaman, 2003). This shirt includes special sensors and interconnections to monitor an individual's vital body signals, and provides a systematic way of controlling the vital signs of humans in an unobtrusive manner (Park *et al.,* 2002).

Wealthy is also a health monitoring system based on a wearable interface with integrated fabric sensors. Its aim is to set up a fully integrated garment system that is capable of simultaneously acquiring a set of physiological parameters in a 'natural' environment. The system targets the monitoring of patients suffering from heart diseases during and after their rehabilitation (Paradiso and Wolter, 2005). Similarly, Lifeshirt is a commercial product that collects, analyses and reports on the subject's pulmonary, cardiac and posture data. It also correlates data gathered by optional peripheral devices that measure blood pressure, blood oxygen saturation, EEG, periodic leg movement, core body temperature, skin temperature, end tidal CO_2, and coughing (Vivometrics, 2004).

The development of integrated heart rate measurement textiles is still a topic of interest and research. There have been several national projects like VTAMN (French National Funded-RNTS, 2000; Lymberis and Olsson, 2002) and currently there are still some others under the Sixth European Framework Programme to investigate the potential of body-worn electronics. The project 'MyHeart' focuses on prevention of cardiovascular diseases with intelligent biomedical clothing (Locher *et al.*, 2005). Its goal is to integrate system solutions into functional clothes with integrated textile sensors. The combination of functional clothes with integrated electronics and on-body processing, creates a sort of intelligent biomedical clothing. The processing consists of making diagnoses, detecting trends and reacting to them (MyHeart Project, 2005).

All these shirts use several techniques for measuring ECG by means of textile embedded sensors in direct contact with the skin. Steel fibres are an appropriate solution for making these sensors as they feel good, have the right conductivity, low toxicity to living tissue, little or no danger of contact allergies because of the very low content of nickel, can be easily washed without losing their properties, and can be manipulated as a textile material (Van Langenhove and Hertleer, 2004). Steel fibres have been used in different ways, wound round acrylic yarns, with a layer of acrylic/cotton fabric coupled with a layer containing stainless steel threads (De Rossi *et al.*, 2003; Engin *et al.,* 2005) or twisted around a viscose textile yarn and knitted (Paradiso and Wolter, 2005). Fibres are woven and knitted, generating a family of sensors called ‘textrodes’.

Nonmetallic solid state conductive polymers can also be used as ECG electrodes. A possible electrode structure can be made of cross-linked poly N-vinylpyrrolidone. The electrode (Lobodzinski and Kuzminska, 1998) comprises a thin strip of polyester film coated on one side with silver/silver chloride. Mühlsteff and Such (2004) describe dry electrodes based on silicone rubber produced using a thermal moulding process and integrated by a sandwich design (rubber–textile–rubber) to measure ECG signals. These electrodes can use sweat produced by the glands for a conductive bridge from the skin to the electrode and have a very good long-term stability due to the chemically inert material.

These systems based on electrodes show signal artefacts induced by the subject’s motion, electrode motion, patient’s skin and cable motion. The influence of motion depends on how the electrodes are fixed to the body and can be greatly reduced by increasing contact pressure. Finding appropriate electrode positions on the body and ensuring appropriate contact pressure will be major tasks in the system design process. Also, the implementation requires that electrodes have sufficient electrical properties, show long-term robustness and should not require any interaction with the end user. Easy integration techniques and low production costs can establish a mass market in functional textiles (Mühlsteff and Such, 2004).

Breathing rate

Breathing rate is commonly measured by means of magnetometers, strain gauges or inductance plethysmography (Martinot-Lagarde *et al.*, 1998). Respibelt (Hertleer *et al.*, 2002) is a fabric sensor made of a stainless steel yarn, knitted in a Lycra® belt, providing an adjustable stretch. By wrapping the Respibelt around the abdomen or thorax, changes in the circumference and length of the Respibelt caused by breathing cause variation in both inductance and resistance. Most studies report that, for long-term monitoring, when only respiration rate is required, there is no significant difference between measurement by strain gauges and inductance plethysmography (Catrysse *et al.*, 2004).

The Wealthy system also contains a prototype of a respiration sensing device that uses impedance to derive the respiration of the wearer (Wealthy, 2002). Lifeshirt® monitors respiration by means of thoracic and abdominal inductive plethysmography bands sewn into a Lycra® vest. In this case, the shirt is functionalised with carbon-loaded rubber (CLR) piezoresistive fabric sensors, used to monitor respiration trace (Grossman, 2003).

Temperature

Body temperature can be measured by textile-embedded thermocouples (Van Langenhove and Hertleer, 2004) or thermistor-based sensors (Teller, 2004; Locher *et al.*, 2005). Temperature-sensitive polymers (amphiphilic block copolymers) offer a change of phase at a tuneable temperature. In these copolymers, the different parts of a molecular chain have different water-attracting properties; in other words, parts of the molecule are hydrophilic and other parts hydrophobic. This polymer can reversibly alternate between a gel structure and a micelle structure (Williams, 2005).

Galvanic skin response

The wearable armband sense wear system measures the galvanic skin response (GSR). GSR represents the electrical conductivity between two points on the wearer's arm. The Armband's GSR sensor includes two hypo-allergenic stainless steel electrodes connected to a circuit that measures the skin's conductivity between these two electrodes. Skin conductivity is affected by the sweat from physical activity and by emotional stimuli. GSR can be used as an indicator of evaporative heat loss by identifying the onset, peak, and recovery of maximal sweat rates (Teller, 2004). This system could be implemented in the textile by means of the previously described textile-embedded ECG sensor techniques.

Skin pH

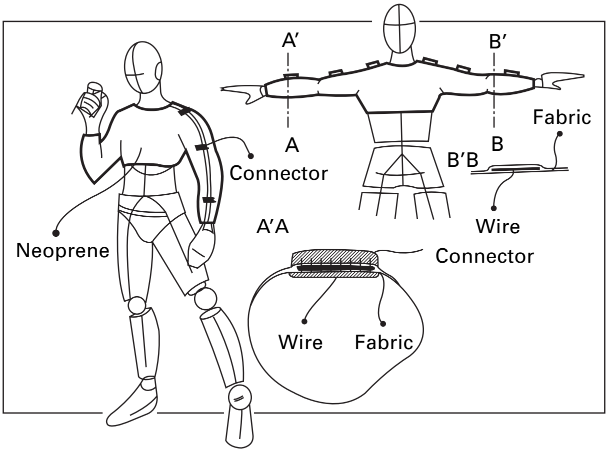
Skin pH is related with cutaneous diseases and its value can be determined by means of embedded pH responsive polymer fibres. A dramatic alteration in the degree of ionisation of the polymer can result in a profound change in the molecular arrangement. This structure is effectively 'coiled' under one condition and 'uncoiled' under another; this is manifested by significant changes to volume, shape and properties (Williams, 2005).

Biomechanical signals

Biomechanical signals are very varied in type and include joint motion, body and foot pressure signals among others.

Joint motion

Monitoring body kinematics has a fundamental importance in several biological and technical disciplines. In particular, the possibility of exactly determining posture may furnish a useful aid in rehabilitation topics (Togneti *et al.* 2005).



20.5 Mobility measurement by integrating accelerometers in the textile. Source: IBV.

Four different approaches have been employed to date for the kinematic analysis of joint motion: attachment of discrete inertial sensors to the textile, inclusion of thin piezoelectric films, manufacturing of piezoresistive fibres and coating of yarns and fibres with CLRs. Accelerometers and gyroscopes are inertial sensors very suitable for attachment to a textile substrate (Fig. 20.5), as they are small, lightweight and reliable (Belda-Lois *et al.*, 2005).

Piezoelectric films can act as shape or angle sensors (Martin *et al.*, 2004). These sensors exhibit excellent motion-sensing capabilities (Edmison *et al.*, 2002), low power consumption, and can be found in a broad range of voltages based on the type and magnitude of the applied stimulus. Piezo-resistive textiles (a combination of conducting polymer and fabric) are useful due to their elasticity, ideal conformability to the human body, and high piezoresistive and thermoresistive coefficients (De Rossi *et al.*, 1999). However, conducting polymer-based sensors are not easily amenable to textile technology (Carpi and De Rossi, 2005). A new generation of high-performance strain sensors has been obtained by coating yarns and fabrics with CLRs, typically consisting of a silicone matrix filled with carbon black powder (Carpi and De Rossi, 2005; De Rossi *et al.*, 2003; Engin *et al.*, 2005). CLRs show, as do PPy sensors, thermoresistive properties.

Interface pressure

Pressure values between body and an interface (i.e. seats or beds) have been widely studied in order to improve users' comfort (Buckle and Fernandes, 1998) and reduce pain or sores in elderly patients. For this purpose, measuring devices integrated into a sandwich-like structure covered by textile layers have been used in practice (Babbs *et al.*, 1990). Following this line of thought, many devices have been patented to measure body position, breathing rate and heart rate using force sensitive resistors, capacitive sensors, piezoelectric sensors and microphones, but in most cases, they were expensive and wired to other devices (Van der Loos, 2001).

The approach to measuring pressure by means of intelligent textiles has taken the form of pressure sensitive mats consisting of a spacer fabric with embroidered electrically conductive patch arrays on both sides (Locher *et al.*, 2005). Each opposing patch pair in the arrays forms a plate capacitor whose capacity changes with the compression force on the spacer fabric. Technological production is becoming ever cheaper and nowadays it is possible to find pressure-sensing textiles such as the Softswitch (Softswitch, 2001), which uses a so-called 'quantum tunnelling composite' (QTC). This composite is an insulator in its normal state and changes into a metal-like conductor when pressure is applied to it. The pressure sensitivity can be adapted for different applications. Using existing production methods, the active polymer layer can be applied to every type of textile structure, knitted fabrics, and woven or nonwoven fabrics (Van Langenhove and Hertleer, 2004).

Foot pressure

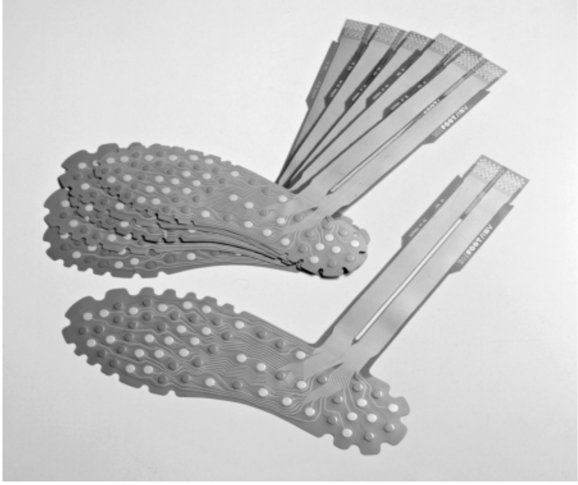
Foot pressure is related to comfort (Chen *et al.*, 1994) and is extremely important in patients with Diabetes Mellitus (DM) and other foot pathologies. Diabetics are prone to foot ulcerations due to neurological and vascular complications. Ulcers appear as a combination of physiological, structural and biomechanical changes and several wearable piezoelectric insoles have been developed in order to study how to reduce plantar pressure (Sarnow *et al.*, 1994) such as Biofoot/IBV (Fig. 20.6).

Other parameters

Closely related to biomechanical signals, but in a more general manner, some other sensors should be mentioned because of their potential interest, namely, force sensors (general applications) and optical deformation sensors.

Force

The properties of piezoelectric materials mean that they can also be used as force sensors (Lane and Craig, 2003; Gould, 2003) in the form of extensometric gauges (De Rossi, 2003). These materials respond to almost any type of magnitude of physical stimulus including, but not limited to, pressure, tensile force, and torsion (Edmison *et al.*, 2002).



20.6 Biofoot/IBV wearable pressure-sensing insoles. Source: IBV.

Deformation

Fibre Bragg grating (FBG) sensors convert energy from mechanical into optical and electrical. FBG sensors look like normal optical fibres, but inside they contain a diffraction grid that reflects the incident light of a certain wavelength (principle of Bragg diffraction) in the direction of origin of the light. The value of this wavelength linearly relates to a possible elongation or contraction of the fibre. In this way, the Bragg sensor can function as a sensor of deformation (Van Langenhove and Hertleer, 2004). A possible use of these fibres as intelligent textiles is integration into flexible orthoses to determine the requirements of the patient or even generating feedback.

20.4.2 Intelligent textiles as actuators

Actuators can perform movements, release substances, make noise, and many other actions. Shape memory materials are the best-known examples; they transform thermal energy into motion (Van Langenhove and Hertleer, 2004) and have a notable importance in the thermo- and hygro-controllability of textile products (Gniotek and Krucinska, 2004). In the following subsections, the three main types of actuating applications in health and monitoring (force application, electrical stimulation and drug supply) will be described.

Force application

Three types of electroactive materials are being used nowadays as actuating fabrics: electroactive polymers (EAPs), dielectric elastomers and carbon nanotubes. EAPs mainly comprise inherently conductive polymers and conductive plastics. The latter are traditional plastics, almost exclusively thermoplastics that require the addition of conductive fillers such as powdered metals or carbon (usually carbon black or fibre). Conducting polymers show a drastic change in electrical conductivity and in the dimensions associated with changes in ionic doping inside the polymer. Conjugated electroactive polymers can exert high forces, much greater than those of natural muscle, which makes them appropriate as orthotic systems. They also undergo volume changes with noticeable variations of elastic moduli when ionic species are forced to penetrate inside their network by electrodiffusion (De Rossi *et al.*, 2003; Engin *et al.*, 2005).

Dielectric elastomers generate strains proportional to the square of the electric field applied between two compliant electrodes, showing high strains, large force densities, low response times and long lifetimes. They suffer the disadvantage of requiring high driving electric fields (De Rossi *et al.*, 2003) that limit their use in clothing. However, it is possible to integrate them into applications such as sheets or in cushion covers to avoid bedsores.

The other feasible option for applying forces, carbon nanotube actuative fibres, is a sheet of carbon atoms rolled up into a tube with a diameter of around tens of nanometres. Their projected superior mechanical and electrical properties (high actuating stresses, low driving voltages and high energy densities) suggest that superior actuating performances can be expected. However, the manufacture of carbon nanotube fibres needs to be much improved in order to produce fibres that can demonstrate all their actuating potentialities (De Rossi *et al.*, 2003).

Electrical stimulation

Electrical stimulation is defined as the use of an electrical current to transfer energy to a wound. The type of electricity that is transferred is controlled by the electrical source. Capacitatively coupled electrical stimulation involves the transfer of electric current through an applied surface electrode pad that is in wet (electrolytic) contact with the external skin surface and/or wound bed. When capacitatively coupled electrical stimulation is used, two electrodes are required to complete the electric circuit. Electrodes are usually placed over a wet conductive medium, in the wound bed and on the skin at a distance from the wound (Sussman, 2005).

Belgium's Centexbel is studying the textile transposition of a known technology for the rehabilitation of paralysed limbs. This process is known as functional electrical therapy. It is based on the stimulation of certain motor functions through electrodes that transmit electrical microwaves. The aim is to integrate functional electric stimulation (FES) motor aid into a textile structure that would offer the patient a degree of user comfort on a completely different level to present devices (European Commission, 2005).

Drugs delivery

From a pharmaceutical perspective, intravenous drug infusion may be the ideal. But for the patient, the downside is pain and inconvenience. Through one single patch on the skin, transdermal drug delivery can be customised to deliver the appropriate medication. Because this method ensures sustained release over time, it provides a steady flow of medication, reduces the risk of side effects and ensures higher patient compliance. For this reason, a material that releases substances and that can be embedded in textiles opens up a huge number of applications. Controlled drug supply systems in intelligent suits can also make an adequate diagnosis. However, active control of the release is not easy (Van Langenhove and Hertleer, 2004).

Microencapsulation technology (microcapsules of phase-change materials – PCMs – e.g. nonadecane) is being used nowadays in thermal clothing to reduce the impact of extreme variations in temperature. As well as being designed to combat cold, textiles containing PCMs also help to combat overheating, so overall the effect can be described as thermoregulation. They can also be used for medical purposes. Textiles that 'interact' with the consumer, reducing stress, promoting comfort and relaxation, are possible through active delivery from microcapsules. For example, encapsulated glycerol stearate and silk protein moisturisers can be embedded into bandages and support hosiery. The materials maintain comfort and skin quality through extensive medical treatment where textiles are in direct contact with the skin. These systems can also be developed to deliver measured dosages of chemical to combat muscle pain or other more serious injuries (Nelson, 2002). Currently the research group Medical Textiles/Biomaterials at the ITA (Institut für Textiltechnik der RWTH Aachen) focuses on the optimisation of a drug release system using degradable non-woven structures and microspheres. Natural hollow fibres and certain man-made fibres are possible microenvironments for bacterial bioreactors. Polydimethylsiloxane (PDMS) cellular microenvironments can be incorporated into yarns and non-woven fabrics to create bioactive fabrics (Wang *et al.*, 2001). PDMS is the most widely used silicon-based organic polymer, and is known for its particularly unusual rheological (or flow) properties.

20.4.3 Intelligent textiles in communication

Several levels of communication can be defined in an intelligent textile, depending on the emitter and the receiver: communication between components (within the textile), communication between the textile and the user (interfaces) and communication between the textile and a data storage system at a certain distance from the user (data transmission). Any kind of communication system must be compatible with comfort, durability and resistance to regular maintenance processes.

Communication between components

Electronic components in intelligent textiles (Gniotek and Krucinska, 2004) can be integrated at three levels. The first level of integration is the use of freely available electronics, connected by inserting the devices into the fabrics. At a deeper level, are the special miniaturised constructions and their composite-like installation in the textile structure, for example between the layers of the product. Finally, the direct installation of p–n junctions on fibres (FE-Fibre electronics) overcomes the limitations (low flexibility, fault-tolerance and cost-effectiveness) of the embedded silicon cores connected by fixed wiring. Weave-patterned organic transistors offers a novel approach to provide interconnection in intelligent textiles (Lee and Subramanian, 2005). In most cases, microelectronic devices are not really integrated into textile structures; they are 'stitched' on the fabric or hidden in the textile structure. Textiles can have 'floating' wires at regular locations across the fabric to allow for attachment of e-Tags (Lehn *et al.*, 2004). e-Tags are small printed circuit boards with connectors specifically designed to be attached to textiles (Martin *et al.*, 2004).

When electronics are added to the textile, the most obvious thing to do is to integrate the connection wires of the different components into the textile. To this end, conductive textile materials are used. In the second generation, the components themselves are transformed into full textile materials (Van Langenhove and Hertleer, 2004). Communication within the suit can be currently possible by either optical fibres (Park and Jayaraman, 2002) that are insensitive to electro-magnetic radiation and do not heat, but signals need to be transformed into an electrical signal, or conductive yarns (Hertleer *et al.*, 2002; Gimpel *et al.*, 2005; Locher *et al.*, 2005). Both have a textile nature (Van Langenhove and Hertleer, 2004) and are used in several prototypes and products.

Several frameworks for the incorporation of sensing, monitoring and information processing devices, such as Georgia Tech Wearable Motherboard (GTWM) have been developed and are still under research (Park *et al.*, 1999, 2002). Some of them are based on integrating wires (Gould, 2003) such as conductive fibres wrapped in a polymer coating in the textile and others are developed using printed circuit board-like conductive layers (Lobodzinski and Kuzminska, 1998).

Communication between the user and the textile

Communication between the wearer and the suit is necessary for passing instructions from the suit to the wearer and vice versa. The level of sophistication of the communication system varies from a simple buzzer to a flexible colour screen. The conducting polymers integrated into a knee sleeve developed by the University of Wollongong (Munro *et al.*, 2003) act as a strain gauge whereby the sensor is stretched when the wearer bends his knee and resistance within the sensor decreases. At a predetermined threshold resistance an audible tone is emitted to alert the wearer that the desired knee flexion angle has been achieved.

More complete information is offered by the WEALTHY system. The WEALTHY Central Monitoring System is a software module interpreting physical sensor data received from the portable patient unit (PPU) and representing them in simple, graphical forms (Paradiso and Wolter, 2005). In this case, although the information supplied is very detailed, it is transmitted via an antenna and it is not visualised on the textile.

The highest degree of integration of communication from the textile to the patient is achieved by the optical fibre flexible screen developed by France Telecom that is completely integrated in the textile (Hatcher, 2002) and the PolyLED (plastic LED by Phillips) (Engin *et al.*, 2005) which can offer the patient complete information. Regarding the transmission of information from user to textile, conductive textile materials and conductive polymers offer a highly integrated solution like that used in Softswitch (Softswitch, 2001) flexible keyboards.

Data transmission

Integrating antennas into clothing is easy because a large surface can be used without the user being aware of it. In the summer of 2002, a prototype of this application was presented by Philips Research Laboratories, UK and Foster Miller, USA on the International Interactive Textiles for the Warrior Conference (Boston, USA) (Van Langenhove and Hertleer, 2004). Regarding communication protocols, different technical solutions have been introduced, ranging from non-standard custom solutions (Polar Electro Oy, 2005; IST International Security Oy, 2005) to standards such as IEEE 802.11 (also known as WLAN) and Bluetooth. These solutions may be used to implement a personal area network (PAN) or home area network (HAN) (Korhonen *et al.*, 2003).

Not only information can be transmitted to the textile but also energy in order to reduce to the minimum the batteries to be worn by the user. An inductive link that provides wireless power transmission and bi-directional data transmission has been developed by ESAT-MICAS and Ghent University.

It consists of two coils and is able to transmit bidirectional data at a bit rate of 60 kbits/s. Simultaneously, 500 mW can be wirelessly transmitted from the base station to the suit at maximum coil separation of six centimetres (Catrysse *et al.,* 2004).

20.5 Summary and future trends

A revolution in the form of how healthcare is delivered to citizens is on the way. Welfare organisations require new approaches that keep the current standards of services while reducing the associated costs. eHealth applications and wearable systems are at the forefront of new technologies to achieve this revolution. The future trend in wearable computing is to integrate electronics directly into textiles for better performance.

There are a large number of medical applications that will clearly benefit from intelligent textile technologies. These applications cover a broad range in complementary explorations (i.e. diagnosis of heart disease), secondary prevention (i.e. SIDS, biofeedback) and treatment/healing (i.e. wearable orthoses, drug delivery). Future medical applications may include sensors that will non-invasively measure blood gases (CO, SO_2, CO_2) and vital signs. The time required for these applications to be on the market depends to a large extent on the available technologies. The level of integration of technology in textiles is a good indicator of the time required to arrive at commercial solutions:

- Level 1 (adapted solutions) is ready to be incorporated in commercial solutions.
- Level 2 (module interconnection within textiles) should appear in the next few years.
- Level 3 (embedding solutions in fibres) will be ready in the mid-term.
- Level 4 (textronics) is still in the primary phase of development, but is clearly the trend in the technological development of smart fabrics.

In order to become technological realities there are still a number of issues that applications based on intelligent textiles must face including:

- Problems arising from long-term use: washability, deformation and interconnections.
- Energy supply: there are currently two trends that may combine to produce integrated solutions to overcome the problems related to energy supply: the increase in performance, and size reduction of current batteries and energy harvesting of the body (Kymissis *et al.*, 1998). A third approach may be the use of distributed power sources in the textile that use electrochemical reactions.

In conclusion, intelligent textiles offer a new range of possibilities for healthcare. These possibilities depend on the development of the technologies, but they are fast becoming a reality. The first applications are already on the market as specialised products, but the development of technologies will widen the range of possible users. Citizens and welfare systems will be the main beneficiaries of this trend. Patients can improve their degree of independence and quality of life through the use of these technologies. Welfare systems can lower their costs associated with hospitalisation and nursing and provide sustainable care in the future.

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21

Context aware textiles for wearable health assistants

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21.1 Introduction

The integration of electronic functionality into clothing offers new possibilities for medical monitoring. Our approach is to develop context aware textiles. Context aware means that textiles sense the state of the user and the environment and recognize situations and events. We combine electronic textile technologies with context recognition and wearable computing technologies in order to achieve an intelligent and at the same time wearable system. In the first part of this chapter we explain the vision of a wearable health assistant and our system concept. Then we describe the recent developments and achievements in the area of electronic textiles, context recognition and wearable technologies. We show how these three research fields can be combined. In the last part we present concrete applications of our wearable health assistants.

21.2 Vision of wearable health assistant

An increasingly important issue for many of today's devices and services is mobility. In particular there is a growing interest in mobile healthcare services such as portable health monitoring systems. The vision sketches personalized health services for everyone in a trusted and natural way, anywhere and at any time. Healthcare is not restricted to clinics or a stationary environment (like at home) but extended to our whole life. With this approach the current issues can be addressed:

- For many patients it is difficult to manage health problems in daily life. Generally there is a lack of motivation and advice for a continuously healthy lifestyle. Widespread problems that could be avoided are, for example, back pain, obesity and stress-related diseases.
- Physicians have only limited tools to assess patients' health status during their daily activities. Diagnosis is restricted to brief contacts with the patients.

- The costs of healthcare are increasing. The focus is on extensive professional treatment instead of illness prevention.

The wearable health assistant could help people to fight diseases by a preventive lifestyle and early diagnosis. Users could take control of their own health status and adapt a permanent healthier lifestyle. This self-management of health makes people more independent, improves their quality of life and at the same time, reduces healthcare costs.

Three main features characterize our vision of the wearable health assistant: monitoring of the physiological parameters, detection of the user's context and giving feedback to the user. Concentrating on non-invasive measuring methods, physiological parameters comprise heart rate and ECG, respiration, EMG, blood pressure, blood oximetry, skin conductance and temperature. But the meaningful assessment of these vital parameters requires the consideration of the current context of the user. For example, rapidly increasing heart rate could naturally be provoked by jumping up a staircase, but if the user has not been moving, it could indicate a dangerous health status. Context awareness includes the user's motion, activity, gestures and also the affective and emotional state like stress and depression. The user's location, both indoor and outdoor, time, weather, the illumination and noise define the environmental context. Apart from the user's activity and environment it is also important to determine the user's social context that means his contact and communication with other people.

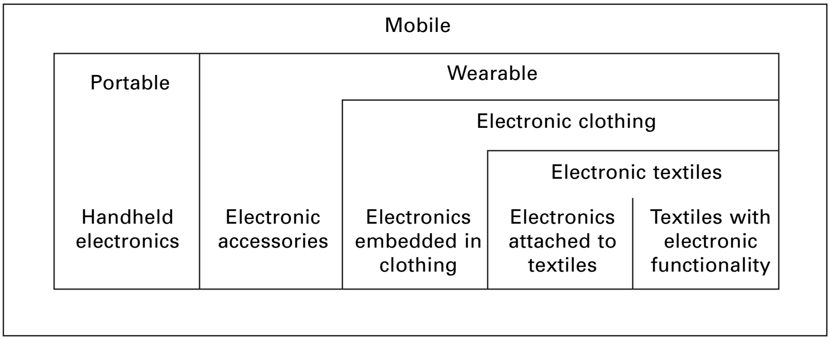
The combination of the vital parameters with the wearer's context, the activity and the sleep patterns together with social interactions paint a picture of the user's health status. To facilitate the feedback and interface between the individual user and the wearable health assistant we propose a 'life balance factor' (LBF) as a plain health measure and generally understandable indicator, especially for medical laypersons. The LBF summarizes the current health status; it indicates changes and calls on a consultation if health parameters are moving to a critical range.

Weiser's visionary view (Weiser, 1991) of an invisible and pervasive computing world is now coming to fruition, where tiny autonomous systems, consisting of sensors, signal processing and transmitting units, possibly as small as a grain of rice, are scattered in the environment. Radio Frequency Identification (RFID) tags are the forerunner of this vision; attached to a variety of daily artefacts, these electronic markers enable the detection of their location and also provide information about the objects to which they are attached. The impact of a computerized environment on personal healthcare varies from monitoring of people with cardiac risks (Gouaux *et al.*, 2002) to home care for elderly living alone (Korhonen *et al.*, 2003).

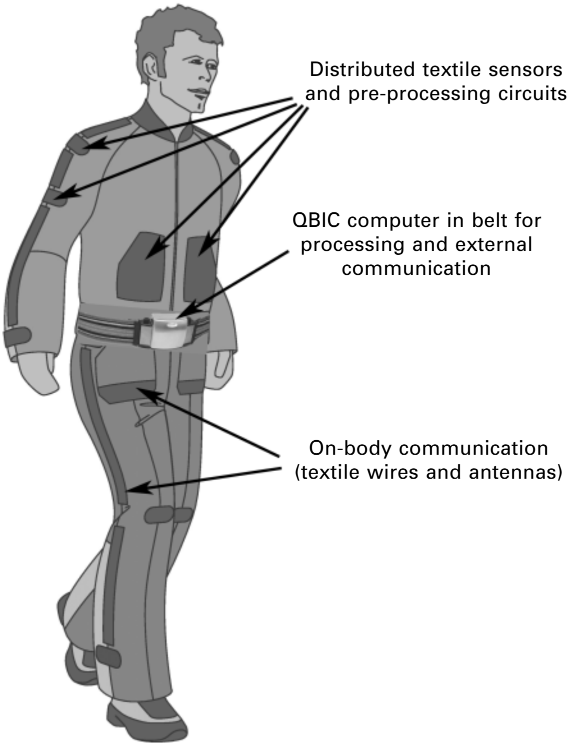
21.3 Approach

For the realization of continuous health monitoring we need on-body electronics (Kirstein, 2004; Lukowicz *et al.*, 2004). Figure 21.1 shows different approaches to on-body electronics, handheld electronics, electronics in accessories, electronics in clothing and finally electronic textiles. In recent years advances in miniaturization, wireless technology and worldwide networking have enabled the development of many portable (hand-held) devices such as cell phones, organizers and laptops. But until now electronic devices on the market are still bulky and inconvenient to use and especially in the medical field rather home-based than truly mobile. The first step to wearability has been made by embedding electronics into accessories like watches and belts. The HealthWear armband by BodyMedia (www.bodymedia.com) monitors, for example, the calorie balance of the user. The next step is to use clothing as a platform for electronics. This idea offers many advantages especially in the medical field because of the direct contact and continuous interaction between the garment and the user. Another important aspect is the comfort of wearing, as humans prefer to wear textiles rather than heavy and hard boxes. Clothing allows integrating the system unobtrusively and conveniently into the daily life of the user. Simply hiding electronic components in pockets or seams is a possible solution. The Lifeshirt by Vivometrics (www.vivometrics.com) is an example of medical clothing where the fabric acts as a carrier of conventional cables and electronic devices. Using the textiles themselves as electronic components goes one step further and is a new approach to the next generation of on-body electronics.

We believe that a wearable assistant as described in our vision can be achieved only by context sensitivity as described above and by a modular system concept. The modular system concept means that we use different integration methods to embed the system into the user's outfit depending on the functionality and the cost of the components. People wear many different



21.1 Approaches to on-body electronics.



21.2 System concept of the wearable health assitant.

clothes and select their outfit according to their activities. Only cheap components with task-specific functionality (e.g. sensors) should be permanently mounted into the garment whereas more expensive general-purpose devices such as processors should be detachable and usable with different outfits. For distributing sensor functionality all over the body and for having direct contact with the skin, electronic textiles offer the best solution. Therefore we embed textile sensors as well as pre-processing circuits and communication facilities into the clothing. Processing devices and components for external communication can be centralized and embedded into accessories (such as belts and watches) or hand-held devices (such as mobile phones). This combination of smart textiles with miniaturized electronics is depicted in Fig. 21.2.

21.4 Electronic textile technology

Textile technological developments have created a whole range of so-called 'smart fabrics' for many applications. The concept of smart materials describes the ability of materials to sense and react to external stimuli. However, most of the advanced textile materials like breathable, fire-resistant or substance-releasing textiles cannot be considered as smart because they do not adapt their functionality to the environment. Hence they are not context-aware as required for the wearable health assistant. Textile materials that can store heat when it is warm and release the heat again when it gets cold (phase change materials) react to a change in environment and therefore possess a low level of context sensitivity, but they have no active control. It is, for example, not possible to regulate the temperature of the clothing according to the user needs. Such an active control is necessary for healthcare applications but it requires an electronic system that processes the sensor data and 'decides' about the reaction. This need for electronics in textiles induced a new research field 'e-textiles'. Considering the opposed properties of electronics and textiles a merging of both seems to be impossible. Nevertheless, the first results show the potential of this idea (Kirstein *et al.*, 2005).

There are two possible ways to create textiles with electronic functionality. Miniaturized electronic components can be attached to fabrics if their size does not reduce comfort. Using electrically conductive fibres and fabrics is the second approach. In this case the textiles do not just act as a substrate but as electronic components themselves. In the following, we describe the latest developments in e-textile research.

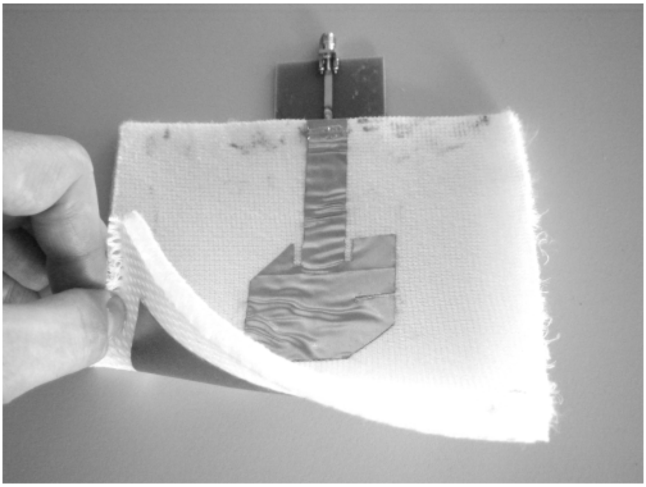
21.4.1 Textiles for communication

Some early approaches to use textiles for communication are described in Marculescu *et al.* (2003). One of the biggest problems was that the fabrics lost much of their typical textile properties due to the embedded thick wires. Our aim was to achieve high-performance signal lines made from conductive textiles that have the same look and feel as conventional fabrics. Several types of conductive fabrics already exist and are applied mainly for shielding and antistatic applications. By developing measurement and simulation methods those textiles can now be optimized for data transmission.

The first systematic studies of the electrical properties of textile transmission lines were carried out by Cottet *et al.* (2003). The proposed textiles are fabrics with copper fibres in one or two directions and with different polyester yarn fineness. The variety of fabrics opens a wide range of possible transmission line topologies and allows finding a configuration that fits potential target applications. Using wire pair configuration the achievable characteristic impedances lie between 120 Ω and 320 Ω. To study the influence of fabrication tolerances, the textiles were modelled with an EM-field simulation tool. The simulation results showed that with the given geometry variations an accuracy of ± 5% to ± 10% for the characteristic impedances is achievable. High-frequency network analyser measurements were performed up to 6 GHz. The extracted frequency characteristics revealed that the dielectric and ohmic losses do not determine the line insertion loss. The loss is mainly influenced by a non-uniform impedance profile along the lines up to the half-wavelength and by coupling to parasitic modes above this frequency point. This results in cut-off frequencies of 1 GHz for 10 cm long lines. Good signal transmission for a 100 MHz clock signal was proved through 20 cm textile lines. Experiments showed also that a grounded copper fibre between two neighbouring lines reduced crosstalk from 7.2% to 2.8%. To conclude, conductive textiles provide potentials in signal transmission in addition to EMI shielding and power supply. Textile transmission lines can be used to create a network infrastructure in clothing and to connect different distributed components of a wearable assistant.

Another important ingredient of a wearable assistant is the connection to a wireless network. For this purpose, textile antennas were developed that guarantee flexible and comfortable embedding into clothing. Wearable antennas presented by Salonen *et al.* (2000) and by Massey (2001) are partially based on textiles possessing an inverted-F shape that results in a stiff structure. Other textile antennas described by Tanaka *et al.* (2003) and by Salonen *et al.* (2003) are designed as rectangular patches with a protruding probe feed and only linear polarization. Antennas such as presented in Salonen *et al.* (2004) utilize fabrics only as substrate whereas the patches and ground planes are copper foils.

We developed antennas that are purely textile and flat (Klemm *et al.*, 2004). Those textile patch antennas are designed for Bluetooth in the frequency range from 2400 MHz to 2483.5 MHz. The design of this antenna is inspired by the build-up of printed microstrip antennas and consists of a three-layer structure; electrically conductive fabrics act as ground plane and antenna patch and are separated with a fabric substrate. The conductive fabric should have a homogeneous resistance below 1 Ω^2. Therefore we used a metallized fabric that was plated before weaving or knitting. Using a knitted fabric leads to a highly bendable and deformable structure. From a manufacturing point of view, the knitted structure is a drawback because precise shaping as well as assembly of the antenna without warpage are difficult. The manufactured antenna shapes finally achieved a geometrical accuracy of about ±0.5 mm. Another undesired effect of the knitted fabric is a change of the sheet resistance when the structure is stretched. Conductive fabrics that are woven possess better electrical performance, but bending of such an antenna is limited. The textile substrate provides the dielectric between the antenna patch and the ground plane and needs to have a constant thickness and stable permittivity. We chose a spacer fabric with a thickness of 6 mm and performed humidity measurements covering a range from 20% to 80% relative humidity within a temperature range of 25 °C to 80 °C. The measurements showed that permittivity variations are negligible compared to measurement uncertainty. Alternative substrate materials are felts and foams.



21.3 Textile Bluetooth antenna.

During the design process of the antenna it was important to achieve a flat and wearable structure; that also means a planar antenna feed. We designed a microstrip feedline and applied insets in order to adjust the antenna's input impedance and to avoid losses due to mismatch between feedline and antenna. Additionally, a microstrip feedline does not increase the height of the patch antenna and maintains wearing comfort when integrated into clothing. We designed linearly and circularly polarized textile antennas and proved a good directivity that minimizes unnecessary radiation exposure to the human body and radiation losses. The textile antennas feature a 10 dB bandwidth of 200 MHz on average. Even when bent around a radius of 37.5 mm resembling a mounting on a human upper arm, Bluetooth specifications can be assured. One of the textile patch antennas is shown in Fig. 21.3.

21.4.2 Textiles for signal pre-processing (System-on-Textile)

We believe that conductive textiles offer an even greater potential than just being used as cables or antennas. Such fabrics manufactured with high precision allow complex wiring structures. Along with the proper assembly technology for electronic components and sensors, entire electrical circuits can be embedded into the fabric. We call this technology 'System-on-Textile' (SoT). Using fabrics as substrates for electronic circuits instead of rigid circuit boards enables the placement of small circuits for signal pre-processing close to the sensors. In this way we can distribute sensing functionality all over the body without affecting wearing comfort.

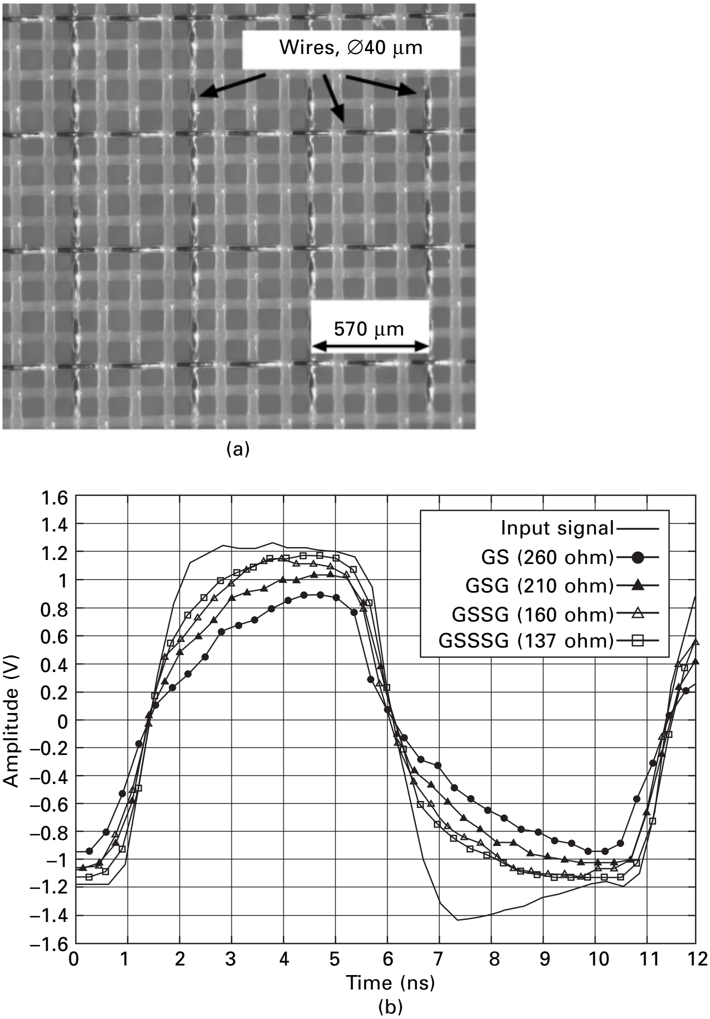
Suitable textile substrates must support electrical routeing structures. The newly developed woven fabric with thin insulated copper fibres provides our platform for electrical circuits. This fabric is manufactured by Sefar Inc., a producer of precision filters. From an electrical point of view, precise yarn distances within the fabric are required in order to achieve satisfactory electrical performance. Secondly, yarn distances need to be small to meet the pitches of the electrical components. On the other hand, the fabric should be fine, light and maintain typical textile properties. Nevertheless, manufacturability of the fabric with the desired materials has to be considered.

After several iterations, we achieved a hybrid fabric consisting of woven polyester yarn (PET) with an exact diameter of 42 microns and copper alloy wires with a diameter of 50 microns. The hybrid fabric with a mesh opening of 95 microns (+/– 10 microns) and an opening area of 44% is shown in Fig. 21.4. Each copper wire itself is coated with a polyurethane varnish as electrical insulation. The copper wire grid in the fabric features a spacing of 0.57 mm (mesh count in warp and in weft is 17.5 cm^{-1}). The combination of PET yarn and copper wires requires a special weaving technology, which includes two yarn systems in warp and weft direction (3 PET wires and 1 copper wire) with separate tensioning systems. We positioned our hybrid fabric with its weight of 74 g/m^2 as interlining. Its application field is therefore very versatile. The fabric represents a compromise between preserving textile properties and copper wire density, i.e., electrical connectivity. To our knowledge, such a precise hybrid fabric consisting of PET yarn and copper wire is unique.

In order to build circuits on the fabric, we need the technology to mount electrical components and interconnect them through the fabric utilizing embedded copper wires. The desired wiring structure can be established by connecting crossing copper wires at their intersections and by cutting the wires at certain locations. Since the wires are insulated against each other, the insulation needs to be removed at these intersections to enable electrical connection. Altogether, three manufacturing steps, as shown in Fig. 21.5, are required to create such an electrical connection.

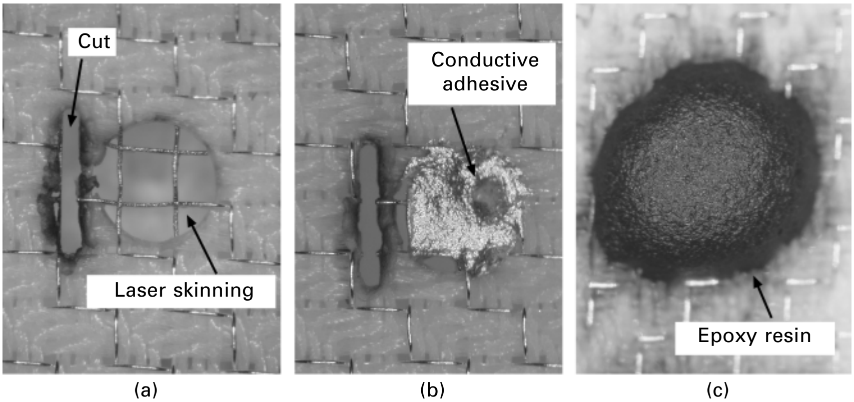
1. coating removal and cutting of the copper wire using laser light at defined locations
2. assembly of the electrical components and interconnecting of the skinned wire sections with conductive adhesive
3. adding epoxy resin to the electrical components and intersections as mechanical protection.

These three steps form the building block for defined wiring structures in fabrics. They can be manufactured in automated processes using equipment for printed circuit board (PCB) fabrication. This assembly technology is described in more detail in Locher *et al.*, (2004, 2005).



21.4 Conductive textile (by Sefar Inc.).

Electrical components usually feature a solid and rigid body whereas fabrics are soft and drapable. Thus, the placement of components onto the fabric requires special attention resulting in an additional trade-off between textile and electrical properties. From a textile point of view, the placement should be done such that drapability and softness are preserved. In other words, the components must not be placed too close together. On the other hand, the electrical wiring should be short in order to avoid electrical losses and noisy signals. In contrast to earlier developments by Virginia Tech and Infineon (Marculescu *et al*., 2003), we were able to mount electrical components directly onto the fabric and interconnect them through the fabric over an



21.5 Manufacturing of wiring structures in fabrics.

arbitrary wiring structure. Utilization of this technique is only enabled by the high precision of our hybrid fabric.

The Sefar Petex hybrid fabric combined with our assembly technology opens a promising new perspective for flexible electrical circuits in the field of e-textiles. The technology enables textiles to be used for processing and sensing tasks and for displays such as those needed in applications for medical monitoring, smart interior fabrics and drapable advertising media. Additionally, the textile properties can be adapted to the application requirements by deploying of different finishes.

21.4.3 Textiles for sensing

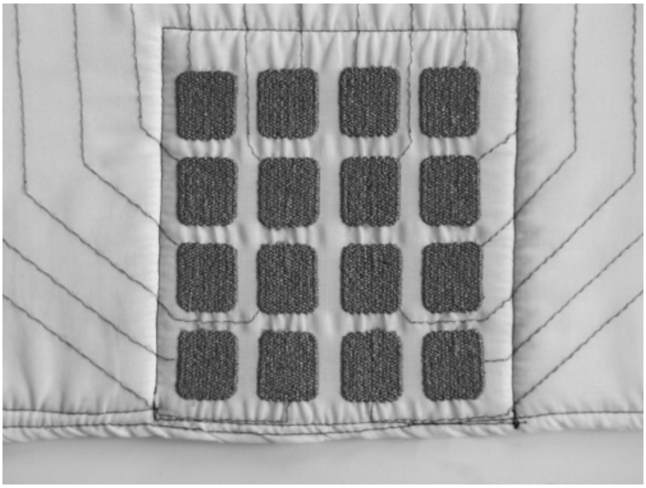
The next step in e-textile research is to use fibres and fabrics not just to transmit but also to transform signals. Conductive textiles that change their electrical properties due to environmental impact can be used as sensors. Typical examples are textiles that react to deformation like pressure sensors and stretch sensors and measure body movements, posture or breathing. Further parameters that can be measured with textiles are, e.g., humidity and temperature. Textile electrodes can replace conventional electrodes for heart monitoring or electrical stimulation (Kirstein *et al.*, 2003). Apart from measuring biometric or environmental data, textile sensors can also act as an input interface as, for example, textile touchpads.

Textile pressure sensor

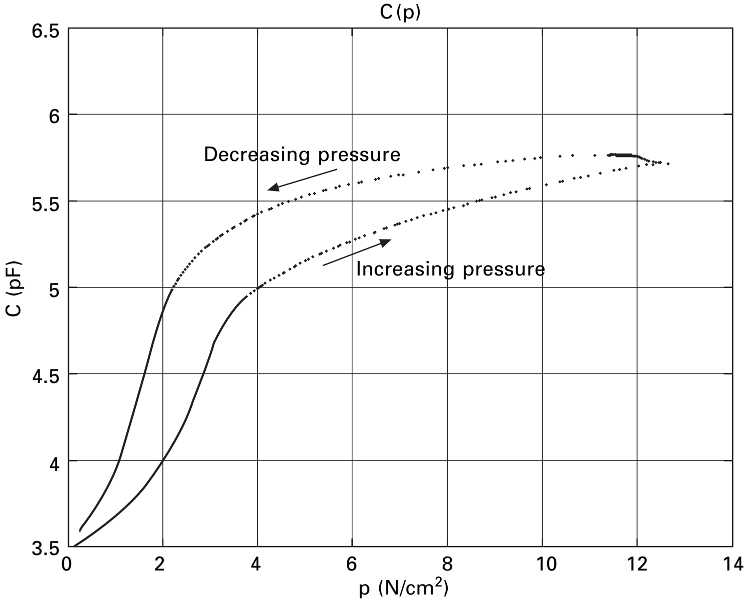
Pressure sensors that are made from textiles have many attractive features for wearable applications. They can cover a large three-dimensionally shaped surface area and detect pressure without reducing wearing comfort. Apart from acting as input interfaces they can measure pressure distribution during sitting or lying and even detect body movements due to pressure changes in the garment.

ElekTex (www.eleksen.com) is a laminate of three textile layers. Conductive fibres in the central layer are locally compressed allowing conductive contact between the top and bottom layer. Softswitch (www.softswitch.co.uk) is made of conductive textiles with a thin layer of elastoresistive composite material (Quantum Tunnelling Composite QTC) that reduces resistance when compressed. The Sensory Fabric (patent US2003119391) contains conductive and insulating yarns in a woven structure that can create electrical contact at yarn crossing points when compressed. All these structures act as switches and do not deliver pressure values. We developed a pressure sensor mat consisting of a spacer fabric with embroidered electrically conductive patch arrays on both sides. Sitting posture and risk of bedsores (decubitus) can be detected using such a mat on seats and beds. The textile pressure sensor is shown in Fig. 21.6.

Each opposing patch pair in the arrays forms a plate capacitor whose capacity changes with compression force on the spacer fabric. Although the capacity is reciprocal proportional to the distance between the patches, the capacity versus pressure is highly nonlinear. Firstly, the compression force nonlinearly depends on the compression distance. Secondly, the permittivity of the spacer fabric (dielectric) increases when compressed since air becomes displaced. Additionally, relaxation of the spacer fabric shows a hysteresis effect as depicted in Fig. 21.7. Using the Preisach model this behaviour can be described, so that the measurement of pressure distribution over a fabric area becomes feasible.



21.6 Textile pressure sensor.



21.7 Capacity measurement hysteresis of textile pressure sensor.

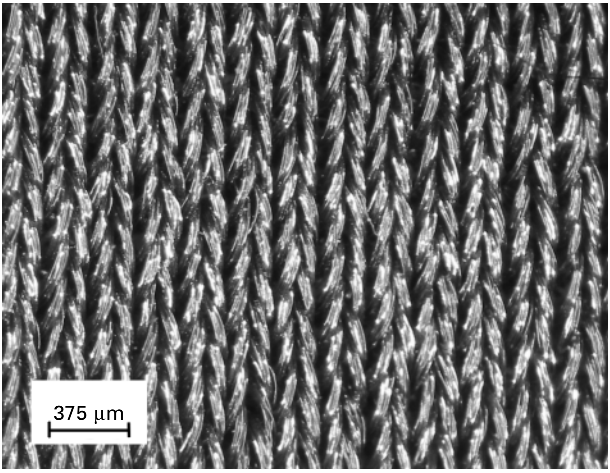
Textile elongation sensor

Possible applications of wearable elongation sensors are, among others:

- posture and motion analysis in sports, medicine, rehabilitation or daily life
- artificial sensor skins for humanoid or animal-like mobile robots
- replacement of acceleration sensors used for context or gesture recognition

The high range (including pre-stretch) of up to 30% strain which is needed for wearable applications as, for example, body posture monitoring, sets wearable elongation sensors clearly apart from other industrial elongation sensors. Additional requirements are comfort of wearing, the need for overstress tolerance and the fact that high elongations have to be measured without stiffening the textile too much.

The most wearable option of making elongation sensors is to use a knitted electroconductive fabric which is stretchable (Fig. 21.8). When such a fabric is stretched, the interconnect topology in the garment changes, and hence resistance changes. Some work on such fabrics can be found in the literature (Pacelli *et al.*, 2001; Scilingo *et al.*, 2003; Oh *et al.*, 2003; Wijesiriwardana *et al.*, 2003; Farringdon *et al.*, 1999; Bickerton, 2003). Mainly fabrics polymerized with conductive polymers, or fabrics made of conductive threads are mentioned. From what is currently published, the following is apparent: these sensors do not perform well because either the response is rather weak

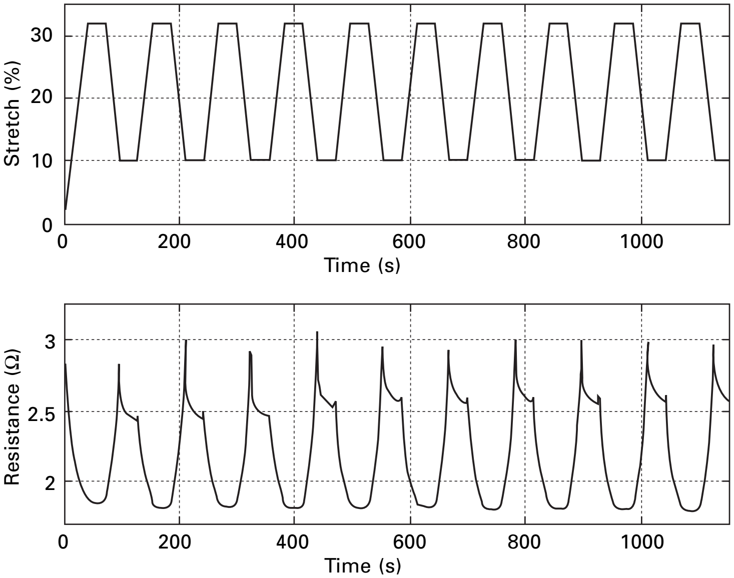


21.8 Conductive knitted fabric.

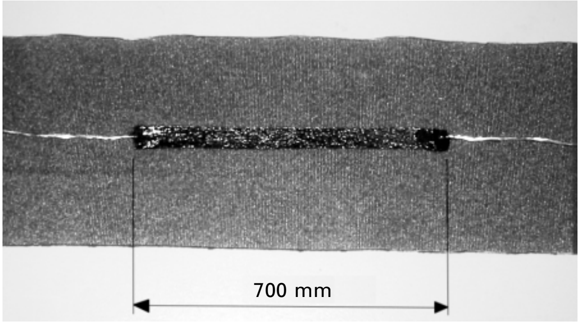
(polypyrrole coated threads/fabrics) or the range is too low (carbon filled rubber coated threads/fabrics). High temperature dependence and dependence of resistance on elongation rate are further problems mentioned for almost all published conductive fabrics.

We evaluated three highly stretchable electroconductive fabrics; two metallized knitted fabrics and a knitted fabric with activated carbon fibres. The general observations are the following: the fabrics show high transient times, peaks when movements start and high hysteresis. Electroconductive fabrics used as elongation sensors are wearable, but the transducer qualities are poor (see Fig. 21.9).

Another kind of wearable elongation sensors can be made by utilizing the piezoresistive effect of electroconductive elastomers. The following options were evaluated: carbon filled silicone rubber coated onto a fabric (Fig. 21.10) and carbon filled thermoplastic elastomer fibers. Carbon filled silicone rubber coated onto stretchable fabrics are extensively used at the University of Pisa (Tognetti *et al.*, 2005). Thereby, a commercial electroconductive silicone rubber product is used. This commercial product was extensively evaluated. It was found that the resistance of this material behaves in a very complex manner when the material is strained. The problems are that there is insufficient repeatability (Fig. 21.11) because the resistance depends on the strain history of the material, there is high electrical hysteresis, the resistance depends on the speed of deformation, the transient time is very high (due to the resistance recovery behaviour), and the general resistance level of the material depends on the applied strain. Resistance recovery is an effect observed in all particle filled elastomeric materials. After a movement, resistance is not constant, but decreases very slowly.

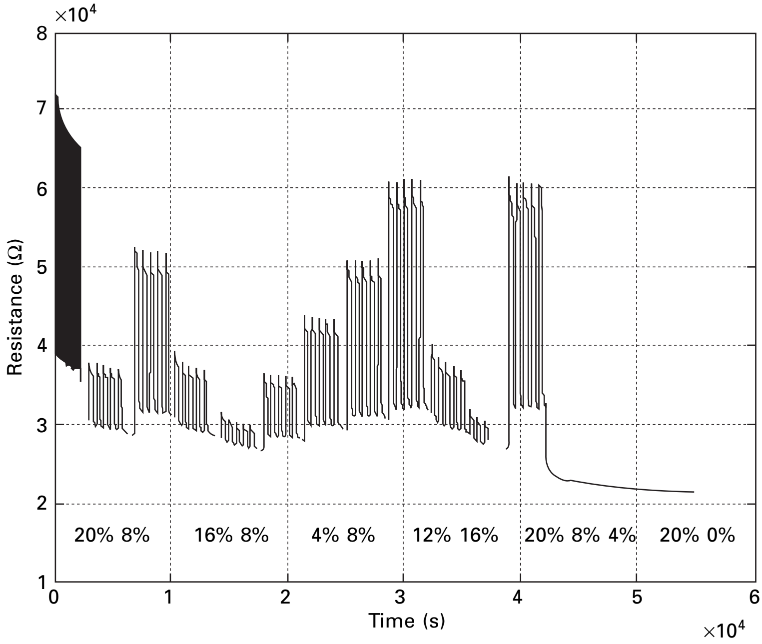


21.9 Periodic elongation and resistance change of conductive knitted fabric.



21.10 Carbon filled silicon rubber sensor.

As an alternative to the commercial conductive rubber described above, six different compounds of carbon filled thermoplastic elastomer fibres were tested. Most of the problems mentioned above can also be found in these materials. However, for some of the compounds, the problems are much less pronounced. The hysteresis problem seems to have been removed completely, but resistance recovery is present as well. It is very important to understand that these kinds of materials are sensitive to all kinds of deformations. Resistance changes not only in response to elongation, but also in response to pressure, shear and bending. Therefore, it is unlikely that these materials can be used as pure elongation sensors. If these materials are integrated into a garment,



21.11 Repeated cycling of carbon filled silicon rubber sensor (with different strain levels, always starting from the pre-stretched zero position).

they will most likely act as general deformation sensors. This is in fact how such materials are used in (Tognetti *et al.*, 2005). In these papers, some work on modelling of these materials and on how signal processing techniques can be applied to compensate the excessive transient times is presented. Summarizing, electroconductive elastomers show complex behaviour and can therefore not be applied as elongation sensors without advanced signal processing. Furthermore, it is questionable if all the unfavourable effects can be compensated through modelling and signal processing techniques.

An alternative approach to using purely textile sensors is to mount non-textile structures onto a fabric. A sensor was produced which utilizes an electroconductive fluid as the transducer medium (Küng, 2005). The fluid is filled into a rubber tube which is glued onto the textile. For the experiments an electrolyte was used. The problem with this fluid is that it diffuses from the tube very quickly. Another type of sensor makes use of the changing light transmission through a fabric when it is stretched (Schultze, 2003). A prototype was built and characterized (Küng, 2005). The results of the evaluations done with the prototype are quite promising. There are no transient times, no hysteresis, and also no dependence on elongation rate. The drawbacks of this sensor are the relatively high obtrusiveness compared to the other sensors and the possibly high power consumption due to the requirement of a light source.

Summarizing, the sensors that are made by attaching a structure to the fabric are not as unobtrusive as the sensors that are made of pure textile material. Yet, their transducer performances are better compared to the other sensors.

21.5 Context recognition technology

The recognition of context, that is the activity of the user and the status of his environment, relies on continuously measured sensor data. In Lukowicz *et al.* (2002) recommendations are made about which sensor or which combinations of sensors are appropriate to detect specific context components. The signals of the sensor data have to be pre-conditioned, e.g., converted, amplified and filtered, before the characteristic features like signal energy or moments are extracted. Several methods and tools have been proved for the fusion of the features. The Bayesian decision theory, for example, offers a fundamental approach for fusion and assignment of predefined classes like motion, sleep, etc. Frequently used methods are the kNN-approach, Kalman and particle filter as well as the Hidden Markov Models and Neural Networks. Combining basic context classes affords the classification also of more complex user contexts like stress and depression. As described in Piccard *et al.* (2001), four wearable sensors (muscle activity EMG, blood oxygen SpO2, skin conductance and respiration) have been applied to detect and to classify eight different motions like anger, grief, joy or hate.

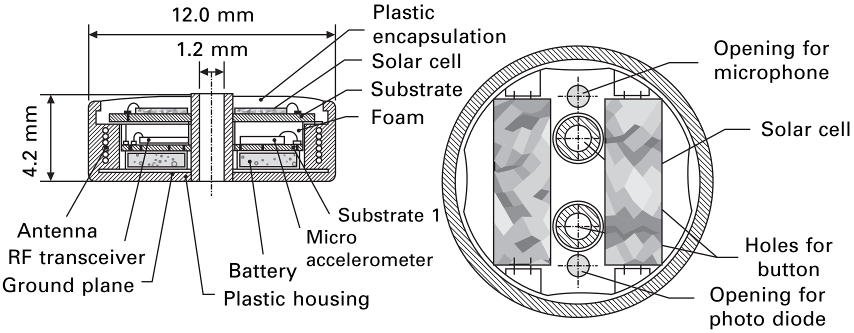
21.6 Wearable components

21.6.1 Embedded microsystems

Recent developments in microtechnology have paved the way to embedding microsystems, either directly in fabrics, or in clothing components like buttons. As a design example Bharatula *et al.* (2004) (Fig. 21.12) shows an autonomous sensor, consisting of a light sensor, a microphone, an accelerometer, a microprocessor and a RF transceiver. A solar cell powers the system even for continuous indoor operation. The two holes allow this system to be sewn in clothes like a normal button.

21.6.2 Accessories

The fusion of the mobile phone, personal digital assistant (PDA) and even the MP3 player into 'smart phones' offers an interface between the personal communication environment and public services. But today's 'smart phones'



21.12 Design of an autonomous 'sensor button': cross-section and top view.

21.13 ETH-QBIC – a mobile computer (Xscale CPU, 256 MB SRAM, USB, RS-232, VGA, Bluetooth) integrated in a belt buckle; the belt houses the flexible batteries and interface connectors.

require manual handling and focusing on the interface. Stripped of bulky IO interfaces and large batteries, mobile computing and communication modules are small enough to be easily carried in a purse or be part of carry-on accessories such as a key chain or a belt buckle as depicted in Fig. 21.13 (Amft *et al.*, 2004).

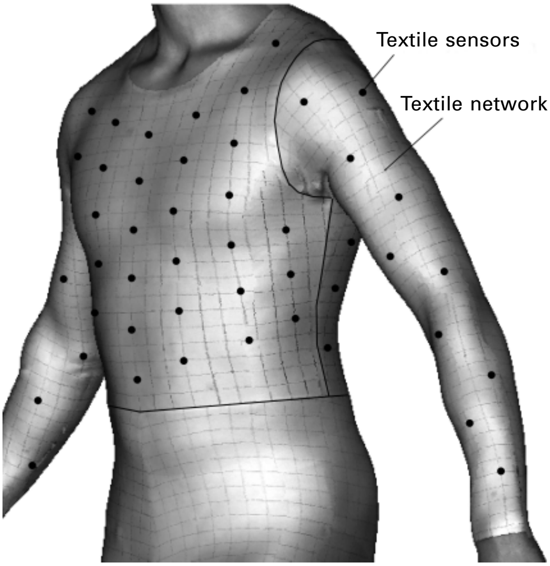
21.7 Applications

21.7.1 Wearable back manager

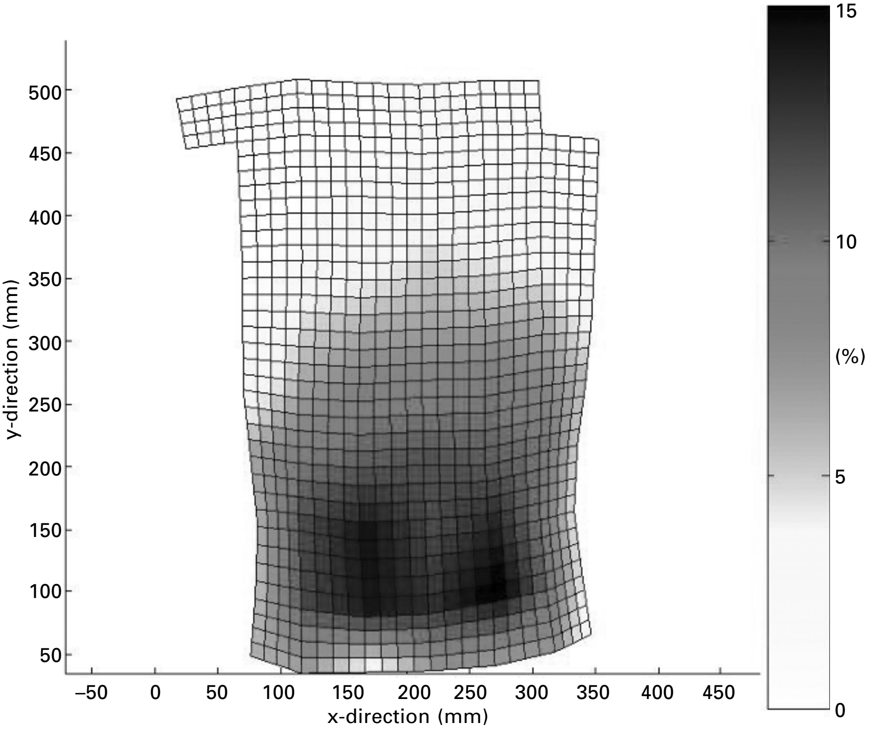
Back pain is often caused by unhealthy behaviour. Personal circumstances and activities can increase the risk of musculoskeletal disorders and accidents. Many occupations are characterized by monotonic body postures, lack of body movements or high stress. European studies reveal that every third employee suffers from back pain and every second complains about exhausting and painful body postures during work. Consequences are often chronic pain, inability to work and long and expensive medical treatment. Prevention of back pain would be much more effective than therapy, but for most people it is difficult to change their behaviour. A personal wearable back manager could help an individual to adopt a healthier life-style in daily life. Using our approach of context-aware textiles the garment could monitor body posture, movements and activities, stress levels and other physiological data.

Figure 21.14 shows the concept of a wearable back manager with distributed sensors that are connected over a textile network. Combining different types of sensors enables detection of situations that are critical for the back. One example of a critical situation is lifting a heavy weight incorrectly. Bending the back instead of the knees can damage the spinal column. In order to know if the situation is critical it is necessary to detect not only the posture of the back but also the lifting movements of the arms, the weight of the object and the bending of the knee joint. Context recognition algorithms as described in Section 21.5 can be used to extract relevant information from the sensor data.

We evaluated the feasibility of measuring back postures with elongation sensors integrated into tight-fitting clothing. We identified regions of high elongations that are characteristic for specific postures (Fig. 21.15). However, existing textile elongation sensors are not suitable for this application as the back manager is intended to be used also in situations with low activity as, for example, sitting in front of a computer. During such activities the elongation does not vary dynamically, so a static sensor output is needed. The textile



21.14 Concept of back manager.



21.15 Example of a measured elongation distribution of the garment on the back.

elongation sensors have to be optimized to fulfil this requirement. Further sensors like pressure sensors, accelerometers, gyroscopes and magnetic field sensors can provide information about the movements of the extremities and pressure changes (e.g. in the shoes). Additional data can come from the objects, for example, by labelling heavy weights with RFID-tags.

21.7.2 Wearable heart manager

The EU-funded project MyHeart (MyHeart, 2004) aims at the reduction of cardio-vascular diseases using wearable health assistants. Cardio-vascular diseases cause roughly 45% of all deaths in Europe; 4 million deaths in Europe, 1.5 million of them in the EU every year. More than 20% of all European citizens suffer from chronic cardio-vascular diseases. Assuming that (only) 5% of the EU population, namely, 19 million persons, will use the MyHeart wearable health assistant, about 60,000 deaths per year caused by myocardial infarctions and strokes could be avoided, saving costs in the range of 12 billion Euros per year.

The project MyHeart focuses on five application fields: improving physical activities, nutrition and dieting, sleep and relaxation phases, stress prevention and early diagnosis and prediction of acute events. The MyHeart wearable health assistant comprises several 'intelligent' clothes with embedded sensors. The data communication with the family doctor, hospital or medical care centre enables an individually matched acknowledgement and health control.

21.8 Outlook

In this chapter we described how the combination of electronic textiles with context recognition technology and miniaturized wearable computers enables a wearable health assistant. Our approach is practicable in terms of modularity and also costs and will allow electronic clothing to become a mass product, one day being affordable for everyone. This trend will have a strong impact on the fashion business. It is not just a chance to strengthen the textile industry by innovation and new market potentials, it also requires a convergence between textile and the electronics industry. That means textile companies have to learn the rules for producing and marketing high-tech products, whereas the electronics companies have to understand the importance of fashion trends.

First implementations of our concept of context-aware textiles in the area of posture training and heart monitoring have been described. Further applications are foreseeable such as prevention of obesity or stress-related illnesses, assisted living for elderly or disabled people, as well as work assistance (e.g. for high-risk environments or remote working). Going one step further from wearable health assistants to even more general-purpose personal assistants will be the next challenge. Such a personal assistant not only monitors the health but also recognizes the needs of the user and provides automatic and active support like a personal servant or friend.

21.9 Acknowledgement

The authors would like to thank Jan Meyer and Corinne Mattmann for contributing their research results.

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22

Intelligent garments in prehospital emergency care

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22.1 Introduction

Prehospital emergency care is an essential part of the chain of survival in cases of trauma or acutely exacerbated diseases. An emergency is a more or less urgent and dangerous situation, because of weakening of some or many vital functions. Prehospital means the period before arrival at hospital. Prehospital emergency care includes all diagnostic and therapeutic procedures carried out by the ambulance (emergency care) team. This team consists of a paramedic and emergency care technician. In some organisations also an emergency physician or nurse can be involved. Appropriate medical control is crucial to guarantee high-quality prehospital care (Holroyd *et al.*, 1986). The organisation of emergency services differs greatly in different countries, and even in different areas of a country (Suserud *et al.*, 1998). For this reason the facts included in this chapter cannot apply to each national organisation. In order to understand the specific features of applications of smart textiles in prehospital care some of its basic characteristics will be described.

The working circumstances in prehospital emergency care are difficult and the tasks are demanding. The ambulance team gets its actual ‘mission’ by alarm centre personnel, the initial information on the particular ‘case’ is based on the alarm call and compiled mostly by someone who is inexperienced in health care. Each case is individual and diagnosis can be initially obscure on arrival at the patient. What has happened, what is the situation, how has it developed and what should be done, are logical questions in this situation. Based on patients described symptoms and signs, a preliminary diagnosis and estimation of degree of urgency are completed, but only on some certainty level. Clinical assessment includes patient’s observations, measurements and palpations. However, these manual operations, based on human sensation, cannot detect deviations from the norm of all vital functions. Human senses can be clarified by patient monitors, which greatly supplement the clinical picture, and also opens new areas for applications of smart textiles and intelligent garments.

22.2 Different cases and situations

Emergency care services provide care and transportation for a range of different categories of cases. There is a scale from extremely urgent, through urgent to non-urgent missions. There is also a great variation in the disease or trauma that has caused the emergency and of which vital functions deviate from normal and by how much. It will be necessary to estimate these deviations from the normal range. If possible, it includes the stabilisation of vital functions and hopefully returning them to a normal level before transportation.

22.3 Circumstances

The location and circumstances of incidents varies greatly. In most cases they occur at home, but often also outdoors in different circumstances. The weather can be very cold, rainy and windy. Also during transportation the patient is often exposed to outdoor conditions. A smart protection against variable conditions is thus a challenge for emergency care services.

22.4 Vital functions

It is important that every organ in the human body has continuously optimal oscillating homeodynamics under the continuous neuronal and hormonal control. These are functions that are essential and vital for wellbeing. With the aid of intelligent garments it is possible to monitor different vital functions, such as ECG, circulation, respiration, EMG and skin temperatures.

22.4.1 Consciousness

Central and peripheral nervous systems monitor and control the body's functions and adapt them to surrounding ambience and its variations. They protect the body against external/internal influences and dangers. A fully conscious person can greatly facilitate the evaluation of a situation and survey its possible reasons by expressing sensations of the body and explaining their development. His/her important protective reflexes are active. Decrease of consciousness level means always decrease of body security linearly with the loss of perception. Then the danger of occlusion of airways increases as well as the probability of aspiration of gastric contents to bronchi.

Degrees of consciousness can be scaled based on eye opening, verbal and motor response (Glasgow coma scale). The opening of eyes can be spontaneous, a response to voice or to pain, or it is absent. The verbal response can be orientated, confused, inappropriate, and incomprehensible or absent. There is practically no instrumental method to monitor the level of consciousness.

22.4.2 Circulation

It is essential that every organ receives continuously enough oxygen and nutrients from blood circulation. Equally important is the removal of waste products including carbon dioxide. This situation requires normal blood volume, cardiac output and optimal circulatory distribution. The heart pumps blood to tissues through a vascular system consisting of arteries, capillaries and veins. Every contraction of the left ventricle creates a systolic pressure wave in great arteries, and the elasticity of arterial walls maintains the diastolic pressure in circulation. Blood pressure varies greatly between individuals and depends on physical activity (Thomas *et al.*, 2005). Blood pressure is necessary to create blood flow to tissues by overcoming the peripheral vascular resistance. Tissue circulation is controlled by dilation and constriction of local small arterioles. The heart acts according to the rhythm dictated by the sinus node. The impulse proceeds through atria to ventricles. Heart rate adapts to circulatory needs in accordance with the stroke volume which is the volume of blood pumped by one beat.

22.4.3 Respiration

Respiration requires rhythmic movements of the thoracic cage. This is necessary for the exchange of alveolar air and interchange of oxygen and carbon dioxide between alveolar air and blood in pulmonary capillaries. As a result arterial blood haemoglobin will be nearly completely saturated with oxygen. Haemoglobin in the red blood cells carries oxygen to tissues delivering part of the bound oxygen in the capillary to adjacent tissues. Alveolar ventilation also removes carbon dioxide from the body that is produced in tissues.

22.4.4 Body temperature

Thermal balance means that the temperature of the body is optimal for organ function. Core temperature, i.e., the temperature in the central inner parts of the body, is maintained within a narrow range, as human beings are homeothermic. In contrary to the core temperature, the temperature in the peripheral parts of the body, such as in the extremities, varies greatly in accordance with the ambient temperature.

22.5 Monitoring of vital functions

With our own senses we can estimate only roughly if vital functions are performing adequately or if they are deviating from the normal level. In some trauma cases the casualty is stained by blood and mud. Moreover, stress can cause a paleness of the face that can complicate visual estimation of the casualty's state. We can greatly augment our understanding of the actual situation of vital functions by recording parameters electrically, which represent cardiac function, circulation, oxygenation, ventilation and thermal balance (Konstantas *et al.*, 2004, Lymberis, 2004). Patient monitoring is based on probes and wires that can measure electric voltage or current, pressure or light flow. The necessary number and location of electrodes (probes) depends on which phenomenon (parameter) is recorded and how exact data are needed.

22.5.1 Electrocardiogram (ECG)

ECG measures voltage differences created by electric discharges in the heart during each cycle. From different leads of the electrocardiogram one can estimate the impulse propagation, heart rhythm, vascular resistance and possible lesions in the heart muscle as well as their location and extension. Myocardial infarction and cardiac arrhythmias can be detected with ECG. This registered ECG represents electric function of the heart and has no direct correlation with the blood pumping action of the heart. The most impressive pathological evidence is given by a difference in present ECG compared with an earlier recorded one. The exact location of ECG electrodes is a prerequisite for the utilisation of the method in morphologic diagnostics. The probes should have a firm skin attachment and should not be allowed to move at all.

22.5.2 Pulsation

Pulsation is a quite informative circulatory parameter in different situations. Pulsation is recorded at the wrist (radial pulsation), at the inguinal channel (femoral pulsation) or at the neck (carotid pulsation). Pulse rate can be counted by pressing lightly with a finger on an artery but this manual method is laborious. As well as the rate in beats per minute, the strength (strong, weak or absent) and rhythm (regular or not) can be detected.

22.5.3 Pulse oximetry

Pulse oximetry is a highly respected measurement among patient monitoring methods (Nuhr *et al.*, 2004). Oxygenation is such an essential and vulnerable function, that a non-invasive method providing reliable information on oxygenation status is more than welcome. At present the measurement is based on the differences in light absorbance between oxyhaemoglobin and reduced haemoglobin. They are measured with two different emitted wavelength lights (Sinex, 1999). The probe is located usually on a finger, light emitter and detector on opposite sides. A specific algorithm calculates oxygen saturation and pulse rate (Barker, 2002, Gehring *et al.*, 2002, Tobin *et al.*, 2002). Moreover, a visible pulse wave can be reproduced on the screen. The amplitude of the pulse wave mirrors circulation changes at the measuring site (finger) and gives information on the peripheral circulation.

In the interpretation of saturation values one must master the oxygen dissociation curve characteristics. As the normal saturation is 95–98%, 92% means an imminent hypoxaemia and at the 90% level hypoxaemia is already real. Changes in oxygenation are fast in many emergency cases, and active treatment of hypoxia is both essential and effective. Pulse wave amplitude is a relative parameter, which strongly reacts to several different stimuli.

22.5.4 Measurements of body temperature

The measurement of core temperature from rectum, tympanic membrane or oesophagus is technically easy. Skin temperature measurements are a totally different entity. Both individual data and their differences serve as valuable material in the interpretation and conclusions. Temperatures and their textile-integrated measuring sensors are intrinsic components of intelligent garments for prehospital emergency care.

22.6 Selection of monitoring methods

In prehospital conditions all actions should be undertaken easily and quickly because of shortage of time and manpower (Birk and Henriksen, 2002). The selection of methods and parameters in patient monitoring starts from the real needs and benefit/effort ratio of the parameter. In each case it must be considered, which of the vital functions are absolutely necessary to evaluate and which parameters are the most informative for the diagnosis and status estimation. This type of intelligently and individually tailored patient monitoring would greatly increase the benefit/effort ratio. At the same time it reduces the flow of information which is also a very important aspect in emergency care.

22.7 Interpretation of monitored parameters

The interpretation of recorded data requires clinical experience, knowledge and good familiarity with the monitoring method and physiological background of the function that it measures. Very seldom the recording expresses directly what the diagnosis is and the actual patient situation. There is a need to interpret symptoms, signs and monitored parameters together and thus obtain a diagnosis by utilizing all relevant means. Correct diagnosis and treatment is the main purpose of prehospital care.

22.8 Telemedicine

Therapeutic decisions require deep expertise in the interpretation of findings. There is clearly a need for teleconsultation to have an expert's advice on line

(Bhatikar *et al.*, 2002). Telemedicine application for prehospital emergency care includes transmission of all recorded data to an expert, who can reconstruct the situation, give the correct diagnosis and send treatment and action advice in real time (Anantharaman and Swee Han, 2001). The essential contents of a patient's chart are anamnesis, status, measurement and recording data, all in structured digital form. Thus an interpretation is possible and reliable for an experienced emergency physician to make therapeutic decisions that are transmitted in digital form as a reply to consultation.

The best solution for the organisation of telemedicine services in prehospital emergency care would be one national expert centre, which would always be ready to add high-quality expertise to emergency care both for ambulance and health centre personnel. In the evaluation of a situation correctly monitored and recorded parameters and their trends are valuable because they can be transmitted to experts' computer screens. The effects of therapeutic procedures can also be followed in real time (Gallego *et al.*, 2005).

Presently, the teleconsultation in emergency care in Finland is limited to suspected myocardial infarctions. Twelve lead ECG is transmitted from the field to the nearest central hospital for evaluation and decision of starting thrombolysis is received back from the hospital before patient's transportation. This practice of immediate action has had a positive effect on the infarction outcome. In ECG transmission usually telefax is used.

22.9 Negative effects of transportation on vital parameters

The aim of prehospital emergency care is to stabilise a patient's state to a safe level, before the start of transportation, if it is possible. In an apartment building, carrying the patient on a stretcher from the upper floors is a physically demanding task both for paramedics and the patient. Carrying the patient in the head-down or up position can seriously influence his/her blood circulation. Elevators, on the other hand, are often so small that the patient must be carried in a sitting position, which can be fatal for the patient. During carrying and transportation the paramedic needs to supervise the situation by continuous patient monitoring, and intelligent clothing would be a valuable resource to detect the dangerous development of a situation in real time.

If the patient is well stabilised at the scene there is no need to drive him/her to hospital with maximal speed. Angular acceleration, acceleration and deceleration of the ambulance vehicle all have harmful effects on circulation (Sagawa and Inooka, 2002). These physical factors can also provoke nausea and vomiting, which can lead to dangerous aspiration of gastric contents into bronchi.

22.10 Patient chart

Presently anamnesis, symptoms and signs, observations and measurements are written on patient charts in analogue form. This form contains also notes on times of dispatch, of arrival at the scene and start of transportation and arrival at hospital. It also includes remarks on therapeutic procedures and medication. It is difficult, however, to include information of continuous monitoring in this written form. Its contents are not in transmittable form. A digital patient chart would be a radical improvement for the chain of information (Meislin *et al.*, 1999). All data would be in digital form as a database in the network, simultaneously available in real time for all involved in this particular patient's care. In this networking, a selected abstract of patient's case history could also be augmented before arrival at the scene. These facts could decisively improve diagnostics in prehospital care. The monitoring system based on intelligent clothing would offer valuable assistance to prehospital care.

22.11 Data security

When patient data and case history are handled, data security and privacy have always seriously to be taken into consideration. There are very strict regulations concerning patient data secrecy, which should be known and obeyed. These secrecy rules should not, however, prevent the patient getting optimal treatment, especially in emergencies. It is also important that only authorised health care personnel have direct access to patient data. If the paramedic asks for advice from a national expert centre, patient identity can be omitted so the interchange of data is fully legal and acceptable.

Because decisions on treatment are done based on values and trends of monitored parameters, they must be highly reliable and real. The treatment decisions also include great responsibility because they concern human health and possibly even life. All artefacts are harmful and potentially dangerous. The chain of information includes many points where the registered data can be corrupted. One of the critical points in this chain is the interface between the human body and the probe, just in the area of smart textile applications. Motion easily causes disconnections in tight contact as well as variations in the mobile net intensity. On the other hand, movement may be one characteristic of the emergency care.

22.12 Day surgery

Post-operative care has fundamentally changed in recent years. Earlier, patients were under close supervision after surgical operations in hospital for days, whereas nowadays some patients are returned home only a couple of hours after completion of surgery. Also new anaesthesia methods and anaesthetics have made earlier discharge from hospital possible. The adaptation of vital functions to so short post-operative observation is demanding. The most critical periods are the transportation home and the first twenty-four hours there. Patients' safety would require established reliable monitoring services after day surgery.

These monitoring services would benefit from a smart garment, which would include sensors, connectors, collector and emitter as a patient interface. The smart collector would continuously record and save trends as well as analyse monitored parameters to detect all impending deviations from normal. These functions require a large amount of artificial intelligence because many factors should be simultaneously noticed. The emitter unit would send the data to a call centre for further interpretation in case a parameter or its trend seems to be suspicious. At this level artificial intelligence inevitably requires support from top medical expertise. The most important is the appropriate response of emergency medical services to every alarming situation (Bhatikar *et al.*, 2002). This post-operative monitoring service is a special short-term application of home monitoring services for elderly ill patients (Dittmar *et al.*, 2004, Prentza *et al.*, 2004). In this way an intelligent garment can enhance the safety and wellbeing of the users and support health care.

22.13 Protective covering

One example of the multidisciplinary approach in the development of better patient protection in health care has been the Ergovaate-special clothing for health and social sector-process at the University of Kuopio during 2001–2003. Its aims have been to incorporate technology into clothing for use in emergency care and first aid by developing a protective covering for injured casualties with integrated patient monitoring and data networking. A new concept for emergency care was developed (Mattila *et al.*, 2003). The concept consisted of three different parts: (i) protection of the patient with rescue covering, (ii) monitoring the vital functions of the patient and (iii) collecting the patient data to a digital patient chart and wireless transmission. The developed and tested prototype of the rescue covering is currently in everyday use in, e.g., rescue services and helicopters in Finland (www.telespro.fi). A demonstration prototype of the patient monitoring and data transmission system was also developed. The protective covering is easy to use in typically demanding emergency circumstances. It does not hamper emergency care procedures. It is possible to touch, examine and treat separate parts the body by exposing only highly the relevant part to the effects of weather.

The selected special materials of the covering allow maintenance after each use. It is easy to remove contaminated blood and other body fluids and to clean the covering without damaging its protective and operating characteristics. This requires a high-class service system. When a casualty is transported to hospital in the protective covering, a replacement covering should be provided for the ambulance staff. This is the only way to guarantee uninterrupted preparedness for prehospital protection against hostile conditions, such as cold and rain. It is also essential that the effective cold protection continues in the hospital during the first hours of stabilisation.

22.14 An integrated monitoring of vital functions

Integrated patient monitoring, data collection and data transmission systems are separate additional modules, which are most important and beneficial in multiple casualty traffic accidents, but they are useful also in single case emergencies. The final goal is a smart integration of probes and cables within the protective textile. A digital patient card would offer obvious advantages in the evaluation of the state of vital functions and their development over hand-written notes. In multiple casualty situations digital patient charts serve as a guideline for setting casualties in priority order to emergency care procedures and transportation. Digital information is not site limited, and is simultaneously available in the same form to all those who understand and need it for decision making. The principal implement in the utilisation of digitalised information could be a Palm PC.

The follow-up of location (accident scene, emergency care tent, local hospital, trauma centre) of casualties in the chain of rescue should be totally automatic, utilising wireless phone networks or special tags and detectors.

22.15 Mobile isolation

Some severe infectious diseases require efficient isolation to protect health care personnel and to prevent infection dissemination and a serious epidemic. The isolation need covers the time from the first suspicion of possible infection, through verification to full recovery. Because care of these infections demands special expertise, they are usually nationally concentrated on special units. As a consequence, suspected cases are often transported long distances and in a critical condition. This requires special preparedness of emergency care both to simultaneously care and isolate, and protect emergency care staff. A seamless isolation of infected patients is the most effective way to prevent the distribution of the problem. Efficient preventive and disinfecting measures are necessary during the whole chain of transportation from home to final isolation room in a central hospital. This includes public stairways, transportation vehicles and long hospital corridors.

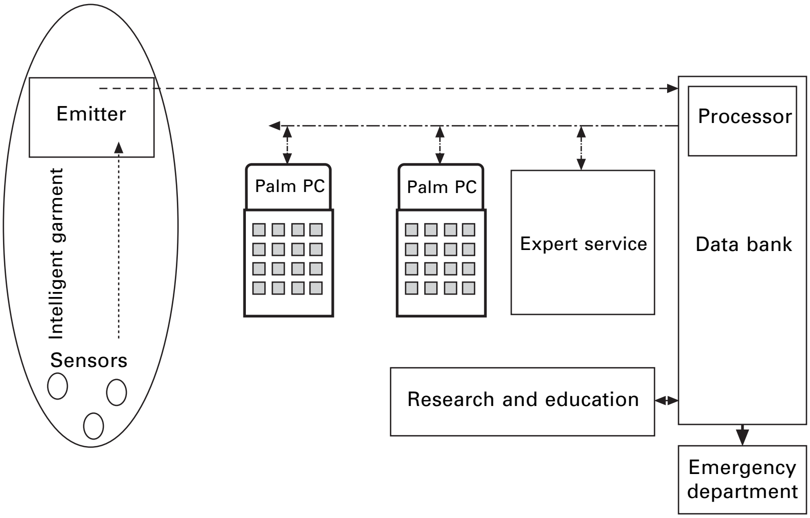
The contamination risk concerns both the emergency care personnel and interior of the vehicle and all pathways the patient is carried through. It is difficult to clean the whole area and impossible to disinfect it. It is much easier is to isolate the patient within an individual containment (Hänninen *et al.*, 2003). Such containment should be clean and ready to use and provide good isolation. It should integrate the opportunities for monitoring and care and be 'portable' to fit in the vehicles and elevators. The protective clothing should be impermeable to microbes and washable at high temperature without losing its benefits. This offers a challenge to materials.

22.16 Optimal smart solution for prehospital emergency care

Because time is the critical factor in sudden emergency situations all the components of the monitoring chain should be instantaneously applicable. As a matter of fact, all the time spent on attaching separate sensors, connecting separate cables, looking at separate screens and trying to get connections for real time devices means delay in diagnosis and appropriate treatment. This point alone provides an opportunity for an intelligent garment to provide all essential components in one entity (Anliker *et al.*, 2004) (see Fig. 22.1).

22.16.1 Sensors

Many of the monitoring sensors can be integrated into textiles, e.g., a shirt or a thorax-surrounding belt so that a firm touch with the body at appropriate



22.1 Schematic presentation of information pathways. The links make patient data available to all participants in medical rescue with the aid of sensors in the intelligent garment. Expert service is connected on line to the accident scene and databank. The databank serves current problem solving and research as well as educational needs.

points can be achieved. Subsequently, the time of probe application would be greatly decreased. The differences in thorax size would provide inbuilt difficulties. All important parameters cannot be recorded from the thorax area, but need some other specific points of recording, e.g., for blood pressure, skin temperatures and end tidal carbon dioxide.

22.16.2 Cables

Different cables and wires that connect probes to collector units disturb measurements and they can become loose and be a source for faults in measured data. Textile integrated electrodes and wireless connections can solve the present problem of lead agglomeration.

22.16.3 Patient chart

Treatment decisions are based on different components of information such as actual anamnesis, case history, status, observations, monitored parameters, procedures and medication. This information should be in easily readable structured form, preferably in graphic phenotype. This entity is called a digital patient chart (electronic patient chart) and it represents a modern high-tech information tool as a completion to an intelligent garment. The same real-time information can be seen on the screen of the Palm PC of the paramedic at the scene, in the emergency department of the responsive hospital and in the experts' telemedicine office. If all digital charts are collected in one national archive, it could serve as a comprehensive source for research, development and education. So far this reliable documentation of different cases in prehospital care has been lacking.

22.16.4 Teleconsultation

The cases in emergency situations are often complicated and the need for expert advice for diagnostics and optimal treatment is urgently needed (Soysal *et al.*, 2005). This requires a standby advice service system, instantly ready to give appropriate medical advice on a wide range of problems. In a small country a national expert centre would be a justified solution to guarantee a high quality of teleconsultation round-the-clock seven days a week.

22.17 Conclusions

The presently available sensor and information transfer technologies make the follow up of the vital functions possible. Nevertheless, only a minimal part of the technically possible applications is in routine use in prehospital emergency care at present. Prehospital emergency care opens distinctive challenges for the application of modern technology and design in extremely demanding conditions. The applied monitoring technique can be decisive for survival through correct diagnosis to appropriate therapy enabling also teleconsultation on line. A partial solution could be an intelligent garment, which would provide integrated probes, cables and wireless connection to Palm PC (mobile PC screen) in one entity (Barnard and Shea, 2004). The adoption of the potentially valuable technologies takes time because of the difficult and multidimensional working conditions.

There is a need for efficient services from alarm to response, whenever intelligent garments are used in home care for elderly sick patients and post-operative monitoring after day surgery. Smart applications for emergency care require multidisciplinary cooperation of top experts in emergency care, in smart textile solutions and monitoring/information technology because end products and organisations should be usable in difficult field conditions.

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23

Intelligent textiles for children

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23.1 Introduction

During the late 1990s the textile sector entered a new era, the one of intelligent or smart textiles. Due to the emergence of new materials, functional textiles were elevated to sensors and actuators, which are among others, required building blocks of smart textiles. Throughout the years however, the definition of smart textiles has altered. Nowadays they are more frequently defined as system concepts merging textile materials and electronics, resulting in a textile with extensive capabilities. Although smart textiles are applicable in a wide range of areas, a great deal of the research focuses on their use in garments. It is obvious that textiles used for clothing are the ideal interface between the human body and external technologies. Moreover, several of these technologies are aimed at facilitating our life. Implementing them into a garment can therefore considerably increase our level of comfort and safety in a non-obtrusive way. This new genre of clothing has been entitled 'smart garments'. They can be applied in areas such as healthcare, protection, sports and leisure.

When used in a medical environment they are often referred to as smart biomedical garments. This clothing typically has monitoring and processing capabilities for bio-physiological signals. Furthermore, advances in telecommunication technologies have led to the development of stand-alone garments. It is clear that a successful merging process between new textile materials and wearable microelectronics enables these developments.

Children especially can benefit from this evolution because today's monitoring methods are not always child-friendly. Generally, children being monitored are prevented from moving freely because wires connect the sensors to the related instruments. By embedding sensors, interconnections, antennas and electronics in the garment, a child-friendly stand-alone suit can be obtained. In addition, the use of embedded textile components guarantees washability (and thus reuse) of the suit.

Based on these ideas, a Flemish project was set up in the late 1990s to develop a smart suit for infants, named the Intellitex suit. A consortium was founded with three partners involved: the Department of Textiles of Ghent University, the Electronics Department MICAS of Katholieke Universiteit Leuven and the Paediatrics Department of Ghent University Hospital. The four-year project was funded by IWT (Belgium), which is acknowledged for its support. The realisation of the Intellitex suit will be presented here.

23.2 State of the art

Smart textiles belong to a fast-evolving research area. New prototypes of smart biomedical garments are unremittingly being presented. It started in the late 1990s when Georgia Tech (USA) introduced the Wearable Motherboard™.[2] This smart shirt was developed for the ambulatory monitoring of soldiers in combat situations. It is a single-piece circularly woven undergarment onto which sensors for monitoring biosignals can be plugged. In addition to monitoring vital signs, the shirt can also detect bullet penetration. The garment itself consists of a grid of optical and electroconductive wires, acting as a 'data bus' through which data coming from the sensors is transmitted to a processing unit. The applied weaving process had to be adapted in order not to have discontinuities in this wiring system. This 'textile motherboard' can be tailored to each individual and provides a platform for a suite of sensors.

Another smart garment WEALTHY was developed by SMARTEX (Italy).[3] It is a wearable monitoring system that fully exploits the possibilities of textiles. Strain fabric sensors, piezoresistive yarns, fabric electrodes and electroconductive interconnections are all knitted into a garment allowing the recording of vital signs such as heart and respiration rate, electrocardiogram, activity pattern and temperature. The sensitive garment is provided with a portable electronic unit that processes and transmits the acquired data.

The Lifeshirt™ by Vivometrics Inc. (USA) is a Lycra vest whose core sensor system is based on inductance plethysmography. The sensor is a sinusoidally arranged electrical wire embedded in a stretchable shirt. In addition, state of the art conventional sensors are used to measure respiration, electrocardiogram, posture and activity.[4] The complete LifeShirt™ system is composed of three parts, a garment, a data recorder and PC based analysis software.

A last biomedical garment that will be mentioned here is a sensorised T-shirt developed within the French project VTAM (Vêtement de Télé-Assistance Médicale Nomade).[5] The T-shirt is equipped with four dry ECG (electrocardiogram) electrodes, a breath rate sensor, a shock/fall detector and two temperature sensors. Sinusoid-like conductors integrated in a textile belt monitor respiration rate, whereas electronic monitoring of the three-component acceleration of the body enables the shock/fall identification. A miniature GSM/GPRS module for signal precomputing and transmission together with a power supply are kept on a belt around the T-shirt.

The enumerated smart biomedical garments are just a limited selection of initiatives in progress. Developments particularly aimed at children, however, are fewer. The Mamagoose pyjama, developed by the Belgian company Verhaert is an example. The baby suit is marketed as a prevention tool for SIDS (Sudden Infant Death Syndrome). Conventional heartbeat and respiration sensors collect data from the infant and an alarm is sent out in case of potential danger.[6] Also the previously described Lifeshirt™ system is available in a paediatric size for children from five years old.

The above-mentioned state of the art smart garments differ in their exploitation of the textile material. Only a few of them use it as a sensing device while many still rely on conventional sensors. In more applications textile material is utilised for interconnections, being woven or knitted into the garment. Nonetheless all quoted research efforts express the feasibility and the great potential of garments to be used as wearable monitoring systems.

23.3 The intellitex suit

The main aim of the research carried out by the Flemish Consortium was to explore new textile materials and microelectronics to combine them in a smart biomedical garment for long-term, continuous monitoring of children in hospital. Babies having to be monitored as protection against SIDS are only one example in which the garment could be applied. The Intellitex suit distinguishes from the Mamagoose pyjama in the more extensive use of textile material.

Children who have to stay in hospital for a while will generally experience this as unpleasant. This is partly caused by the fact that their body is covered with different kinds of electrodes and wiring connects them to monitors. Furthermore, monitors using conventional sensor technology often cause skin problems. The monitoring systems currently in use are generally not really ‘child-friendly’. Recent advances in smart textiles and telecommunication can remedy these shortcomings and provide the small patients with sufficient freedom of movement. The possibility of integrating sensors, data processing units, storage and transmission circuitry and interconnections into clothing means patients will be provided with more comfort, mobility and privacy. Moreover, children will experience wearing smart biomedical clothing as normal, without even noticing they are being monitored.

From the beginning of the project, it was decided to focus mainly on the development of a textile sensor-based system for long-term continuous monitoring of heart and respiration rate, named the Intellitex suit. In contrast to other projects we resolved not to miniaturise and integrate conventional sensors but to exploit the capabilities of textile material as such. Therefore, we adopted electroconductive textiles, particularly stainless steel yarns and structures. These yarns are currently being knitted, woven and embroidered, hence using existing textile technology to apply them into sensorised garments. In doing so the aim of the development of smart textiles was met by exploiting the potential of the textile material such as giving it sensing capacities. Moreover, as textile materials are used to manufacture other required components, integration will increase, resulting in a washable and patient-friendly garment.

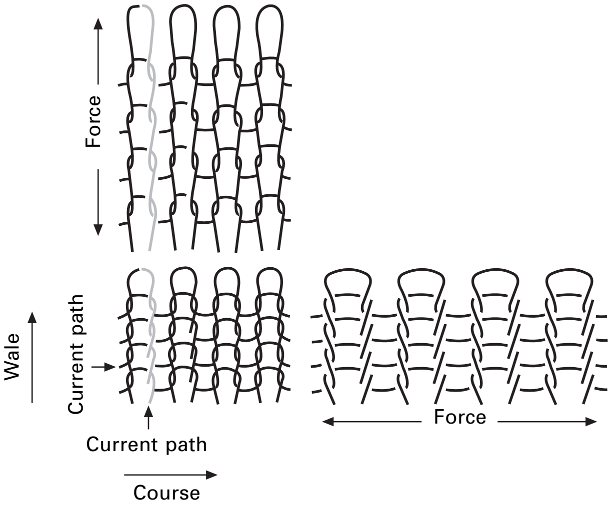
23.3.1 Respiration measurements

A textile sensor for measuring respiration rate was developed.

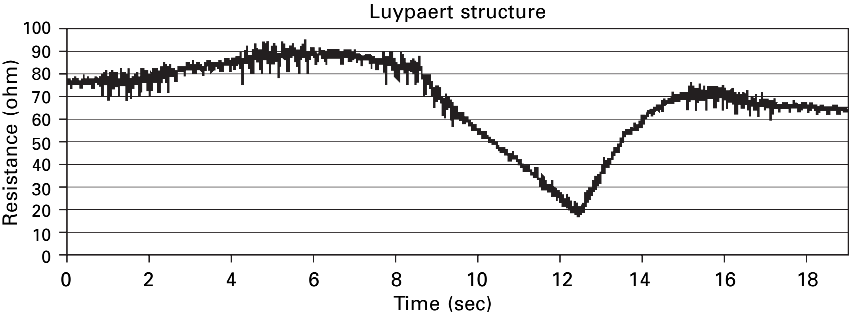
Respiration rate is measured in various ways, such as sensing pressure, detecting CO_2/O_2 concentration in inhaled and exhaled air, applying body plethysmography (inductance, impedance, capacitance, etc.) and using strain gauges. In the framework of this research, textile-based strain gauges were chosen. These are knitted structures consisting of elastic and electroconductive yarns (stainless steel yarns by Bekintex). Knitted structures were chosen on the one hand because of their inherently elastic properties and on the other hand because undergarments are mainly knitted fabrics. By placing the structure as a coil around the abdomen or thorax, a variation in resistance caused by breathing is obtained. Therefore the elastic component is important, allowing the structure to adapt itself to the moving upper body and detecting circumference changes.

Several electroconductive, elastic textile structures were successively tested in a controlled environment to evaluate their ability for long-term use and possible property changes after washing.[7] Based on preliminary research, which proved anisotropy in resistance change for knitted structures, they were stretched in the wale direction, as shown in Fig. 23.1. Resistance changes in course direction are considerably less pronounced because the current flows through one thread uninterruptedly and this conducting path is not changed upon stretching. In wale direction however, the contact points between the successive rows of loops play a prevailing role in the resistance changes. Upon stretching, an increase in contact points results in a decrease of the overall resistance of the structure.

To determine these resistance changes, a dynamic resistance measurement set-up was developed whose core instrument was a yarn tensile tester. It was programmed to perform a continuous cyclic elongation simulating breathing movement. The structure being tested is circularly knitted, consisting of elasthane and Bekinox stainless steel yarn as the electroconductive component. Figure 23.2 shows the resistance change upon elongation of the structure up to 40% and relaxing back to 10%. During the first eight seconds the resistance stays constant, followed by a decrease as the structure is elongated.



23.1 Conducting path in course and wale direction upon stretching.

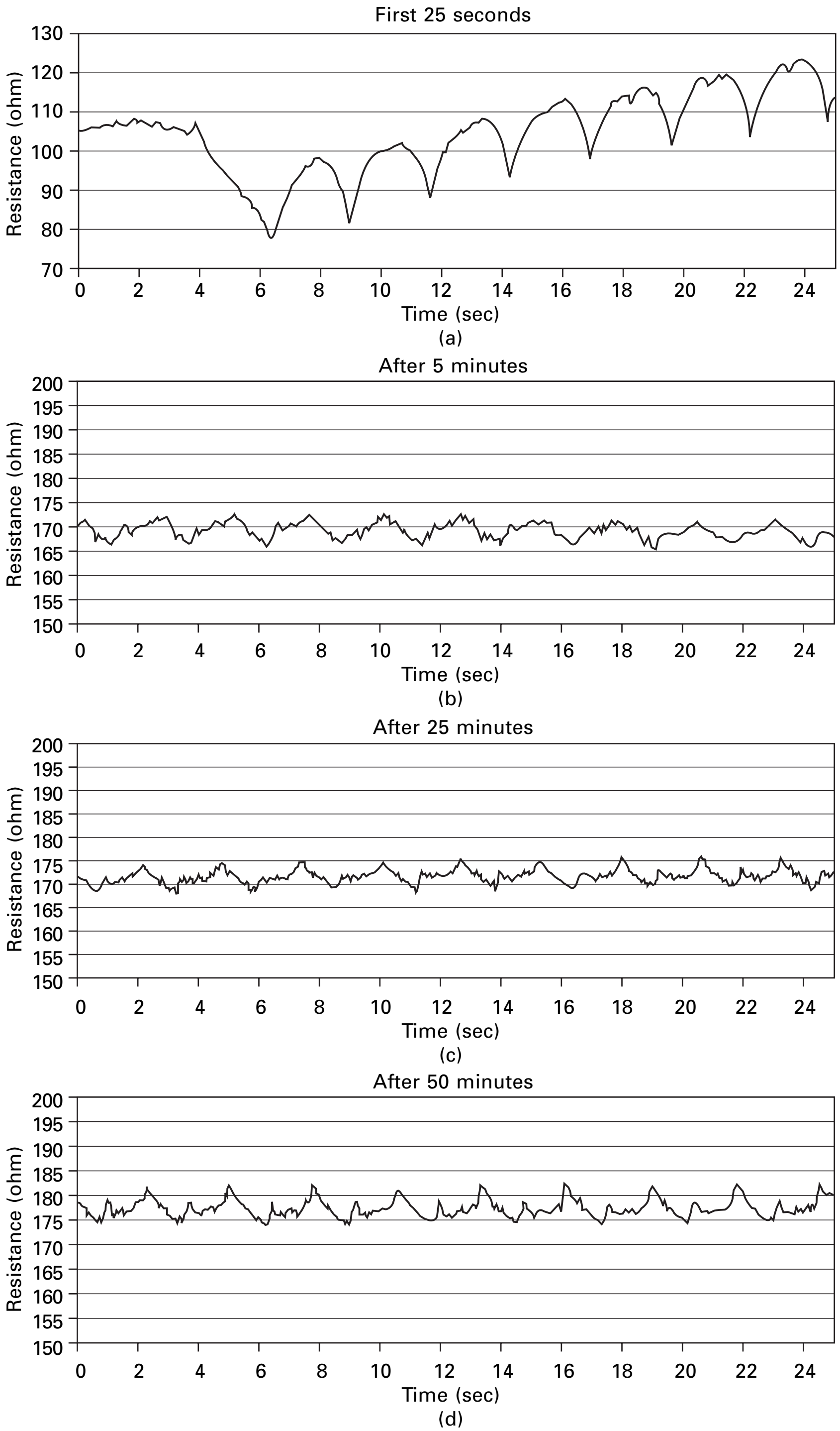


23.2 Change of resistance during one cycle of cyclic elongation.

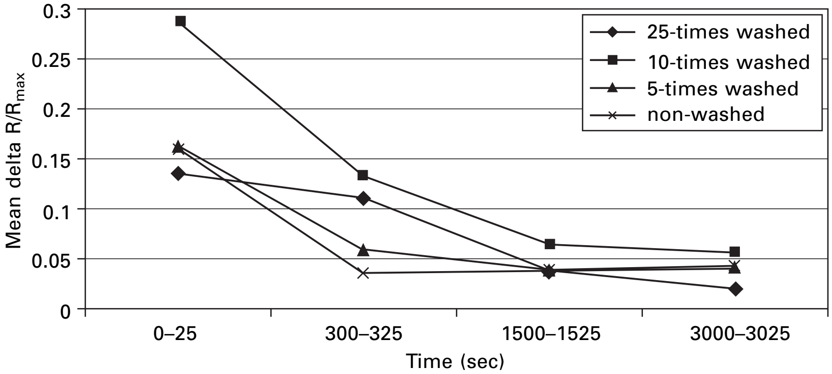
Subsequently the resistance increases as the structure is relaxed to 10% elongation.

This cyclic elongation was repeated for a period of 50 minutes to study the evolution of the signal. Figure 23.3 shows the signal at defined times: after 25 seconds and after 5, 25 and 50 minutes. These graphs show a clear drift of the resistance. The signals' amplitude is slowly decreasing after each deformation cycle but the cyclic motion of elongating and relaxing can still be distinguished.

The same series of tests (50 minutes of cyclic elongation) were performed after washing the structure successively 5, 10 and 25 times in a domestic washing machine. An overview of the results is given in Fig. 23.4. This graph represents the evolution of the relative signal amplitude ΔR/Rmax as a function of time, where ΔR is Rmax – Rmin for each cycle. The graph



23.3 Electrical resistance change during 50 minutes of cyclic elongation.



23.4 Relative signal amplitude during 50 minutes of cyclic elongation at selected time periods for non-washed, 5-, 10-, 25-times washed structure.

shows that there is a tendency for the relative signal amplitude of non-washed and washed materials to equalise over time without damaging the reliability of the sensor; however, the influence of washing on the overall resistance of the structure has to be taken into account. It can be concluded that textile structures containing electroconductive material, are useful as strain gauges when they are carefully engineered and characterised.

23.3.2 Electrocardiogram (ECG) measurements

In order to measure the ECG, textrodes were developed. They are a textile structure constituted of stainless steel yarns (by Bekintex) which may be used in direct contact with the skin. The choice of stainless steel was led by the following properties:

- it is a good conductor
- the fibres have a good touch
- it has a low toxicity to living tissue
- it can be processed as a textile material.

Conventional electrodes are always used in combination with electrogel to establish a good conductive contact with the skin, consequently improving the output signal. However, many patients experience some discomfort since electrogel may cause skin irritation and softening. These inconveniences impose restrictions on the use of this kind of electrode for long-term monitoring. Using textrodes can overcome these limitations because the textile material is in direct contact with the skin hence making electrogel unnecessary.

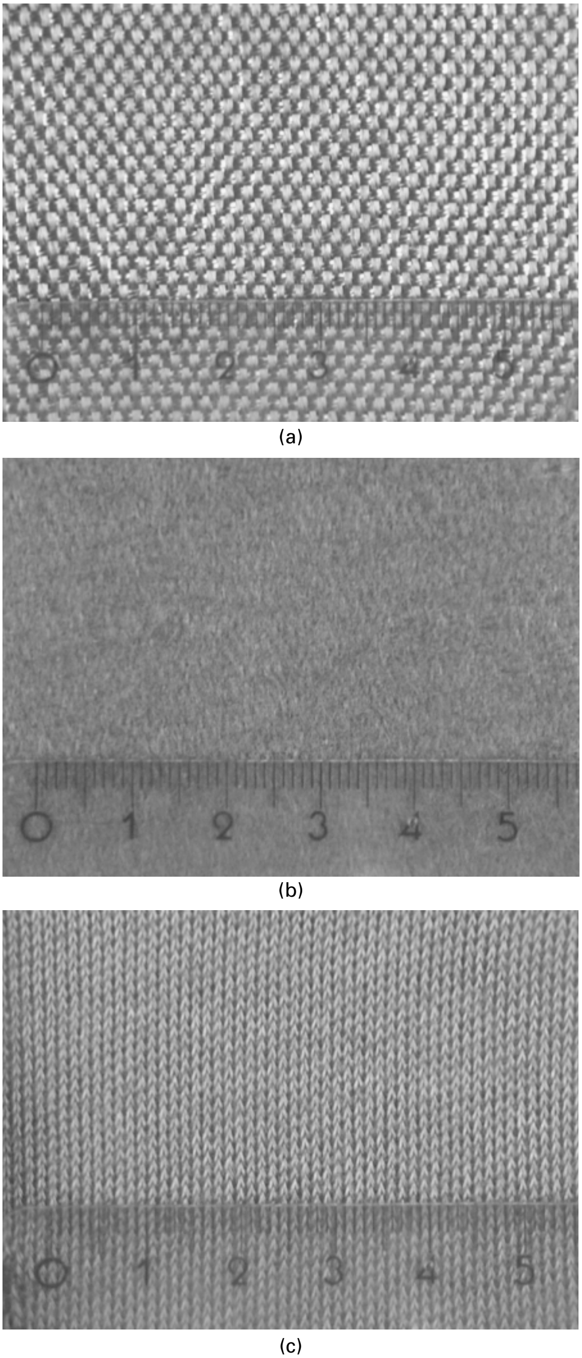
Because of the intrinsic weakness of the potential of the heart measurable at the skin (1.5–3 mV), a close contact between electrodes and skin is of major importance. Therefore elasticity of the garment is a highly required property, improving close fitting of the suit around the thorax. As far as textrodes are concerned, the influence of sweat is experienced as a benefit since it is an electrolyte thus improving the conductivity of the electrical signal towards the electrode.

In recording the ECG and other bioelectric events, the input impedance of the recording system has to be many times greater than the impedance of the electrode/bioelectric system. If this is not the case, not only a loss of amplitude of the bioelectric signal will arise, but also a distortion of the waveform.[8] Moreover, low electrode/skin impedance considerably improves the quality of the measured signal as the noise signal is less amplified. Since the textile electrodes differ to a large extent from the conventional electrodes, the electrode/skin impedance had to be determined. This was done in a frequency domain of 5 to 100 Hz. As was expected, the textile-electrode/skin impedance had an order of magnitude of 1.5 MΩ cm^2, which is much higher than for conventional gel electrodes, where the impedance typically is 10 kΩ cm^2 in the same frequency range.[9] In addition to determining the electrode/skin impedance, a study was carried out on a number of electroconductive textile structures since stainless steel electrodes are available in three structures: woven, non-woven and knitted (Fig. 23.5).

An electrochemical cell was developed to enable a quality evaluation of these different structures when used as electrodes on the skin. The study is extensively discussed in the book *Analytical Electrochemistry in Textiles*;[10] however one topic will be highlighted here. The three textile structures were exposed to four concentrations of artificial sweat (10^{-3}, 10^{-2}, 10^{-1} and 0.5 mol/l) for 24 hours and then analysed to evaluate a possible change in their functioning. The results are summarised in Table 23.1.

It is concluded that the knitted and the woven structure show no significant changes in electrical behaviour as a function of time. The non-woven electrode, however, does reveal a change as for the higher electrolyte concentrations the impedance increases considerably. This might be due to corrosion of the structure or adsorption of species at the fibre surface. The phenomenon is more obvious with very high electrolyte concentrations, which means that the influence is limited. Compared to the knitted and woven electrodes, the non-woven one has a more open structure and a much larger surface area owing to individualising of fibres, which makes it more sensitive to chemical and mechanical interaction. This should be taken into consideration when non-woven electrodes are applied as sensing devices in biomedical clothing. In relation to the sensation of comfort, non-woven fabrics will perform worse since protruding metal fibres will irritate the skin more easily.

In order to have a good elasticity and accordingly an improved contact with the skin, we decided on knitting a sensor integrated belt (Fig. 23.6). Interconnections between the sensors and electroconductive fasteners were knitted in as well. At this stage the electronics were connected to the belt



23.5 Stainless steel electrodes in three structures (a) woven, (b) non-woven and (c) knitted.

Table 23.1 Electrical resistance measured in an electrochemical cell containing knitted, woven or non-woven stainless steel electrodes and different concentrations of artificial sweat. Measurements are taken at different exposure times of the electrodes to artificial sweat

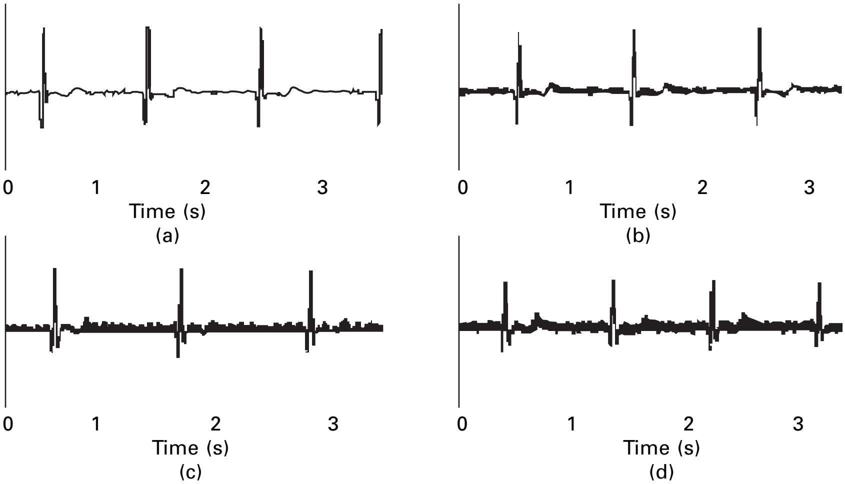
Electrolyte concentration (mol/l)	10^{-3}			10^{-2}			10^{-1}			0.5		
Exposure time (hours)	t = 0	t = 12	t = 24	t = 0	t = 12	t = 24	t = 0	t = 12	t = 24	t = 0	t = 12	t = 24
Knitted	31 610	31 530	31 510	3985	3980	3980	316	316	315	26.1	26.8	27.8
Woven	31 510	31 540	31 495	3989	3980	3982	319	316	316	25.9	27.1	27.2
Non-woven	31 520	31 510	31 540	3981	3978	3.95	315	330	351	25.9	35.0	60.3

23.6 Belt with integrated sensors and interconnections.

through the fasteners. The belt has a double layer knitted structure; the actual sensing material (stainless steel) is only present at determined positions on the inside of the belt, while Viloft/Co^{TM} is used for the other parts and the outside.

To measure the ECG, a three-electrode configuration was used.[11] Two electrodes were placed on a horizontal line on the thorax, while a third one, acting as a reference (named the 'right leg drive'), was placed on the lower part of the abdomen (not integrated into the belt). In order to assess their performance, the signal originating from a conventional electrode (gel electrodes by the company 3M) and the textile electrodes were recorded at the same time. The results of these measurements are shown in Fig. 23.7. Despite the Textrodes generating more noise, the figures show the accuracy of the signal.

The measurements shown Fig. 23.7 were carried out in a laboratory. Later on, clinical tests were performed in an operating room at University Hospital Ghent, Belgium. Anaesthetised children between two and four years old were simultaneously monitored with the textile and the conventional electrodes. The test focused exclusively on the performance of the Textrodes. Because of the ease of handling, a prototype in the form of a belt (as described above) was chosen for the initial clinical tests. The belt can more easily be put on and removed using a Velcro fastener in the front. It also leaves sufficient space on the body to attach other conventional sensors. However, the aim was finally to manufacture a complete baby suit.



23.7 ECG measurements using gel electrodes (a) and (b) and using textrodes (c) and (d).

Clinical tests revealed the following deficiencies:

- The interconnections between the electrodes and the electroconductive fasteners cause problems after repeatedly opening and closing the belt. Metal fibres stick out of the belt and make contact with the surface of the textile sensor. This causes the signal to be interrupted.
- From the tests, it clearly appeared that a good skin-electrode contact has a very great influence on the quality of the output signal (for ECG measurements).
- The Velcro fastener appeared to be unreliable, coming off too frequently during measuring. A fixed fastening system seems to be indispensable.
- The electrical circuit had to be adjusted because the textile electrodes' signal causes the amplifiers to go into saturation.

23.3.3 Wireless communication and energy transmission

In order to extend the autonomy of the textile-based system, an existing inductive link was modified using electroconductive textile material.[12] The implementation of this inductive link has a dual function, enabling wireless bi-directional data transmission on the one hand and power transfer on the other. The data transmission downlink from a base station to the baby is useful, for instance, to change parameters, to determine minimum and maximum respiration rate or to adapt the measuring algorithm to the needs of the patient, while the uplink from the baby to the receiver sends out the measured data. Inductive powering avoids the use of batteries, reducing the volume and enabling continuous measurements. The developed system samples the

ECG signal with a frequency of 300 Hz, while simultaneously a power transfer of 50 mW is transmitted from the base station to the suit.

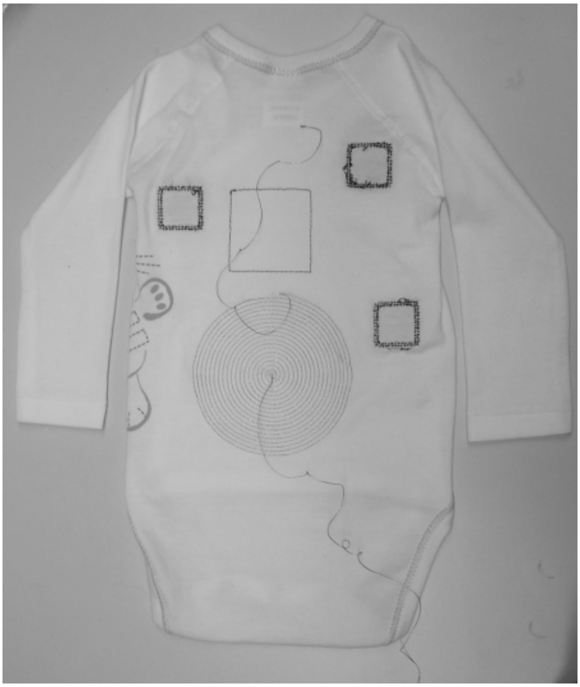
An inductive link requires two coils: a primary coil (the base station) and a secondary coil, operating within a maximum coil separation distance of 6 cm. Since the Intellitex suit is meant for babies, the base station of the inductive link can be hosted in the mattress of the cradle or the bed, while the secondary coil is integrated into the garment. This enables both functions to be realised while the baby is lying in bed. The most suited technique to integrate the coil into the baby suit is embroidery, allowing stitching a very flexible electroconductive yarn with high precision and accuracy on a textile carrier. The embroidering technique was fully exploited to compromise conflicting requirements; as many turns as possible that do not touch each other. Touching turns would create a short circuit while more turns would produce a superior coil. The useful area on the baby suit, however, also restricts the diameter. The ZSK embroidery machine, equipped with a special W-head, succeeded in manufacturing a 20-turns coil with an external diameter of 10 cm.

23.3.4 Intellitex suit: final prototype

Based on the conclusions drawn from the clinical tests, a subsequent prototype was manufactured (Fig. 23.8). This garment hosts more components than the former belt such as the electronic circuit and a wireless power and bi-directional data transmission link are included. In this prototype the electronic circuit is the only non-textile component but special attention has been given to its miniaturisation. To prevent damage through washing, these components have to be removed during maintenance of the prototype garment.

23.3.5 Conclusion

The Intellitex suit is an example of a smart biomedical garment exploiting the potential of electroconductive textile materials. It offers a solution to the disadvantages of conventional techniques. As an alternative to conventional electrodes, both knitted and woven stainless steel electrodes (textrodes) revealed promising results. The main advantage of dry textrodes is the non-irritating and integrating qualities. A disadvantage is the poor skin/electrode contact which is translated into higher demands on the electronic circuit. Therefore the analogue front-end had to be redesigned and optimised. These electronics were assembled on a flexible printed circuit which can be integrated in the baby suit. A set of clinical tests has on the one hand uncovered some practical deficiencies but on the other hand proven the usability of textile sensors. An improved prototype was manufactured. The result is a child-friendly garment that allows small patients to be monitored in the best possible conditions.



23.8 Final prototype of the Intellitex suit.

This work demonstrates that textile materials themselves have a strong potential to be used as sensor elements, interconnections and transmission links in smart biomedical garments. Despite the low quality of the textile sensors, the use of electronics with high requirements provides reliable monitoring. Major benefits are improved patient comfort and reusability of the sensors. Washable packaging of the electronics and durable interconnections remain major challenges to be tackled, not only for the specific system presented here, but for all wearable electronics and intelligent textiles developments. There is still a long way to go to obtain reliable commercial smart biomedical garments.

23.4 Future trends

Not only in this study but likewise in many others the feasibility of smart textiles has been demonstrated and the prototypes proved to be beneficial. The manufacture of truly wearable smart biomedical garments has taken a cautious start, but there is still a long way to go. Slowly these new textile-based products are finding their way into society. Possible problems however should be recognised and overcome by continuously searching for improved materials and technologies. Treating these systems in the way we treat our daily garments is very demanding and therefore a huge challenge. Consequently, evaluation of long-term behaviour, durability and system performance after repeated laundering should invariably be included in the research tasks. Therefore fundamental research has to support the use of these textile materials sufficiently.

Children suffering from diseases such as diabetes, hypoglycaemia and cystic fibrosis could considerably improve their quality of life with the help of smart biomedical garments. Being monitored in a non-obstructive way is of utmost importance to them, not only from a medical point of view but also psychologically. Since they do not notice they are being monitored, it will have a more relaxing effect which will improve the level of comfort. Not being able to pull off the wires of the system will also reassure parents.

In the future garments will detect risks and report them, resulting in an appropriate reaction and thus prevention. In case of hazard, the textile will support, protect and inform. Additionally, during rehabilitation, the textile will deal with the administering of medication through the skin as well as, e.g., performing physiotherapy. The textile will likewise follow up the recovery process and adjust the applied treatment. When exploiting the many advantages of textiles, such as large contact area with the skin, permanent availability and comfort, much physiological data will be collected in a non-invasive way through the garment fabric. This might lead to a more complete clinical picture and consequently new medical insights, enabling the formulation of a patient's medical profile on the basis of which anomalies can be detected. All this is not yet within reach but current multidisciplinary technological developments progressively head towards that direction. Hence, as technology is gradually provided, smart textile systems for children will become available; adapted and accepted as a second active skin and enhancing their level of comfort and well-being.

23.5 Acknowledgements

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24

Wearable biofeedback systems

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24.1 Introduction

Biofeedback systems are becoming increasingly popular due to their non-invasive nature and the beneficial effects they provide both as rehabilitative devices and training tools. However, biofeedback systems have typically encompassed large, rigid electronic devices best used when an individual is stationary or required only to move slowly through a small range of motion. Integration of inherently conducting polymer coatings onto textiles has created new non-rigid biofeedback options in the form of textile sensors. When combined with conventional but wearable electronics, these unique textile sensors can be integrated directly into existing clothing and equipment without changing the material properties or functions of these items and without interfering with normal human motion. The result is truly wearable systems capable of providing immediate biofeedback to the wearer on a set of pre-determined conditions. This innovative technology has been used to develop the Intelligent Knee Sleeve, a wearable biofeedback system able to provide immediate, individualised and objective feedback to the wearer about knee flexion angle. The Intelligent Knee Sleeve is currently used in landing training programs to assist athletes to learn how to land correctly to prevent injury as well as in rehabilitation programs. This chapter describes the concept, design and use of wearable biofeedback systems, focusing on the development of textile sensors and their integration with functional electronics to specifically monitor joint motion using the Intelligent Knee Sleeve. Other applications of this technology for rehabilitation, technique modification and injury prevention are also highlighted, as well as proposed advancements of this technology to ensure its optimal use in today's society.

24.2 Is there a need for biofeedback technology?

Biofeedback training is the use of electronic instruments for subliminal learning to change the body's response in order to improve performance or health, such as during rehabilitation following injury or illness. The field of biofeedback training is burgeoning as it is safe, non-invasive and pain-free and its efficacy and long-term benefits are well documented in the medical literature (Middaugh and Pawlick, 2002; Chiotakakou-Faliakou *et al.*, 1998; Lake, 2001; Barthel *et al.*, 1998; Parekh *et al.*, 2003; Wiener *et al.*, 2000). Often used to alter brain activity, blood pressure, chronic pain, muscle tension, heart rate and other bodily functions normally beyond voluntary control, biofeedback can be provided in various ways, including visual (e.g. a flashing light), auditory (e.g. an audible tone) or tactile (e.g. vibration) forms of feedback. For example, muscle biofeedback involves placing electrodes on the skin overlying muscles of interest and recording the electrical signal generated by these muscles. Feedback pertaining to muscle activity, such as an audible tone to indicate when muscle intensity has reached a desired level, can then be provided to individuals for a wide variety of applications, such as teaching muscle relaxation for the treatment of headaches (Cinciripini, 1982), preventing or treating occupational overuse syndromes (Thomas and Vaidya, 1993), eliciting muscle contraction during strengthening exercises (Storheim *et al.*, 2002), treating incontinence (Jundt *et al.*, 2002) or during rehabilitation following a stroke (Moreland *et al.*, 1998) or surgery (Draper, 1990). As the role of biofeedback is expanding across a broad range of fields such as sport, recreation, rehabilitation, performance of daily living activities and industry, advancements are vital to ensure biofeedback technology can accurately monitor human performance and provide reliable and valid feedback about select aspects of this performance to the user during dynamic motion.

24.3 Are there problems with current biofeedback devices?

The original systems used to provide biofeedback were typically immovable systems of massive size due to the feedback modality and the need for data processing, memory and power supply. These devices were restricted to applications where individuals were stationary or performing slow movements through a restricted range of motion in the vicinity of the biofeedback system. More recently, portable devices have been designed to provide feedback during human motion, such as heart rate monitors and some muscle biofeedback machines. However, these devices are predominantly made of relatively bulky, rigid components that can interfere with, or alter, the wearer's natural motion during dynamic tasks and rarely provide real-time feedback, particularly of joint motion. Therefore, the challenge confronting those involved in monitoring human function is the ability to design truly wearable systems, systems that are conceived as 'unobtrusive as clothing' (Engin *et al.*, 2005, p. 174), although capable of sustained real-time data processing during dynamic forms of activity.

24.4 Can we provide biofeedback for joint motion?

For practitioners involved in directly evaluating and modifying human motion, the ability to monitor the biomechanics that characterise human performance in the field, such as joint motion, and then to 'feed' this information back to the wearer in real time so the performer may modify their motion during the actual skill to achieve the desired outcome, has been elusive. Currently, coaches, trainers and medical personnel typically 'eyeball' the performance of their athletes and/or patients and 'guess' whether the correct motion is being used before providing verbal feedback to change their movement patterns. Alternatively, they can use highly sophisticated apparatus for biomechanical analysis of human performance, such as optoelectronic motion analysis systems. However, this equipment is often extremely costly and requires both significant expertise to use and extensive data processing (e.g. manual analysis of video images) before meaningful information can be relayed back to the performer. Furthermore, although this information can be relayed using both visual and verbal forms of feedback, it is usually not received in real time. Alternatively, to receive real-time feedback, performers may be required to view a monitor whilst performing a task, restricting the movements that can be performed. Other devices, particularly those that are attached to the user's body, such as electrogoniometers, can be used to provide feedback about joint motion in real time. These devices also have the benefit of being able to provide the feedback through audible or tactile forms during the performance of dynamic activities. Despite this benefit, electrogoniometric-like devices are often inappropriate as they have rigid components that do not conform to the user's body shape, thereby interfering with their natural motion during dynamic movements and, potentially posing a safety hazard to the user. Furthermore, care must be taken when providing tactile biofeedback as these feedback forms may induce muscular response, potentially leading to injury.

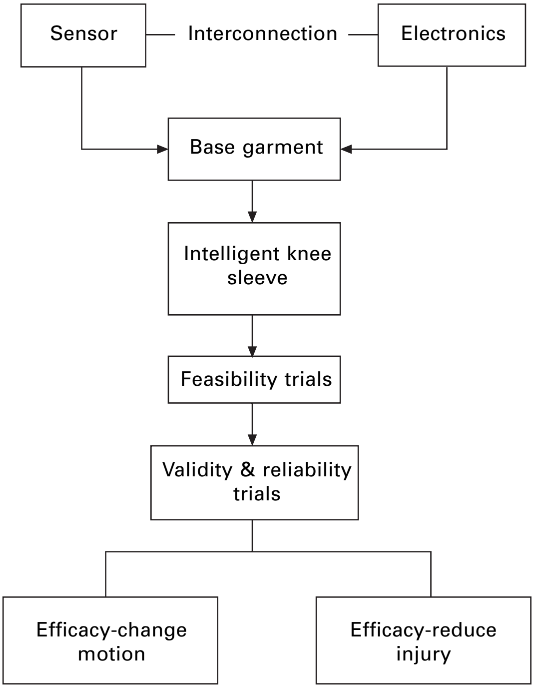
Advances in textile technology have seen the emergence of electronic textiles, which can overcome the limitations traditionally encountered with rigid biofeedback devices. For example, conductive coatings can be used to transform fibres, yarns or textiles into electrically conductive materials through electroless plating; evaporative deposition; sputtering; chemical, electrochemical or admicellar polymerisation with a conductive polymer (Lekpittaya *et al.*, 2004); and filling or loading fibres and carbonising (Meoli and May-Plumlee, 2002), without significantly altering existing textile properties. These conductive textiles have strain-gauge-like properties which, in preference to conventional, non-textile strain gauges, are wearable, have a wide dynamic range (De Rossi *et al.*, 1999a; Fletcher, 1996) and are relatively inexpensive. Electrically conductive metals such as ferrous alloys, nickel, stainless steel, titanium, aluminium, copper and carbon can also be applied to textiles to produce highly conductive and wearable sensors. However, these metals are brittle and may potentially damage fibres within a knitted textile structure (Kaynak *et al.*, 2002). Specific coating procedures must be developed to overcome problems with adhesion and corrosion resistance.

In comparison, textiles coated with conductive polymers, namely polypyrrole, polyaniline or polyterthiophene, have excellent adhesive and non-corrosive properties (Kuhn, 1993) and are less expensive than metallated textiles. When combined with parallel advances in the miniaturisation of conventional electronics and computing, and with a concomitant decrease in size and power consumption, these unique textile sensors are ideal as novel, non-rigid wearable systems capable of providing direct biofeedback with respect to joint and segmental motion. That is, they can be integrated directly into existing clothing and equipment without changing the material properties or functions of these items and without interfering with normal human motion. Therefore, these wearable textile biofeedback systems are considered superior to traditional biomonitoring systems as they contain minimal rigid components, conform to body shape, are extremely light, do not impede human performance, are safe to be worn during physical activity and are of low cost. Furthermore, due to their simplicity in design, these devices have multiple applications in sport, recreation, industry and when performing activities of daily living.

Independent of the application, wearable biofeedback systems require the optimal integration of three components, which are attached to a base garment, namely the textile sensor, functional electronics and the interconnections between the sensor and electronics (see Fig. 24.1). These components will be discussed as isolated components in the following sections and then how they are integrated to form the Intelligent Knee Sleeve.

24.5 The development of a functioning wearable textile sensor

Electronic sensors are devices that detect and then transform measured quantities of physical phenomena into an electrical signal (Engin *et al.*, 2005; Gniotek and Krucinska, 2004). The ideal electronic sensor to monitor human motion is a wearable textile strain gauge that has a wide linear dynamic range with appropriate sensitivity, a fast response time (low time constant) enabling use over the frequency range of interest in biomechanical measurements and an initial resistance compatible with the electronics to be used. The sensor should also generate minimal resistive force upon stretching over the frequency range of interest and have little or no hysteresis in either the electrical or mechanical response. Ideally, these wearable sensors should also be robust against external physical, electrical and electromagnetic disturbances as well as impervious to sweat, moisture, washing processes, temperature, mechanical impacts, repeated bending, compression and light



24.1 The steps involved in the development and assessment of a wearable biofeedback system.

Table 24.1 Properties of the ideal textile sensor for use in a wearable biofeedback system

Properties of the ideal wearable sensor
Appropriate textile substrate
Ability to control initial resistance (coating conductivity)
Appropriate sensitivity
Large linear dynamic range
Small response time
Minimal resistive forces and limited hysteresis
Robust and immune to environmental effects
Compatible with simple electronics

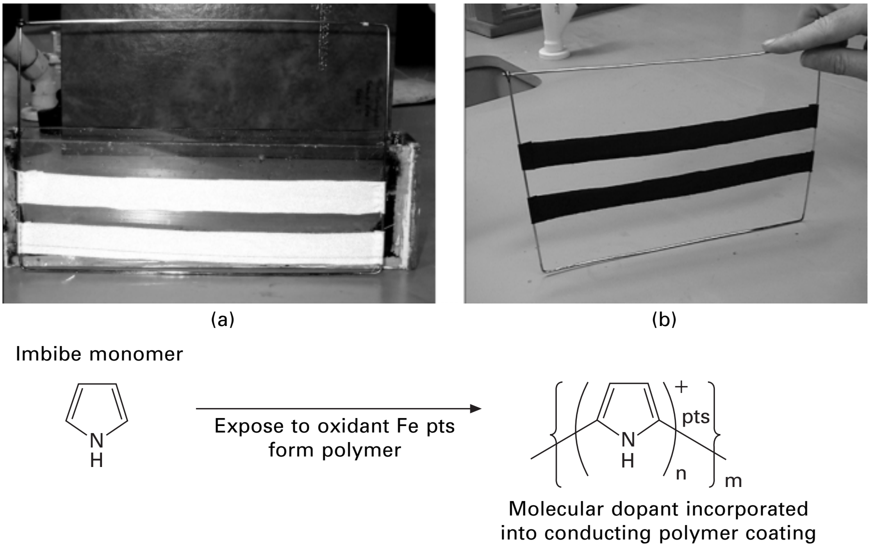
(Gniotek and Krucinska, 2004; Engin *et al.*, 2005). In addition, it is vital that wearable sensors are designed for low power consumption. Therefore, conducting polymer-coated textiles offer several attractive features with regard to their use as wearable electronic sensors to monitor human motion. The ideal properties of a wearable sensor, as summarised in Table 24.1, with respect to the performance of polypyrrole-coated nylon lycra, are discussed in the following sections.

24.5.1 Textile substrate

Nylon lycra has proven to be an excellent textile substrate for wearable strain gauge sensors when compared to other commercially available textiles (Campbell *et al*., 2003). This composite textile substrate exhibits very low resistive forces such that when worn, body movement is not impeded. Nylon lycra is also easily coated with conducting polymers using the Kuhn (1993) method involving *in-situ* polymerisation on the surface of the textile (see Fig. 24.2). Use of this *in-situ* polymerisation technique readily obtains thin, uniform, adherent coatings (see Fig. 24.3) as each of the individual fibres is separately coated with no fibre bonding, such that there is no resulting deterioration in the mechanical properties or the handle of the fabric.

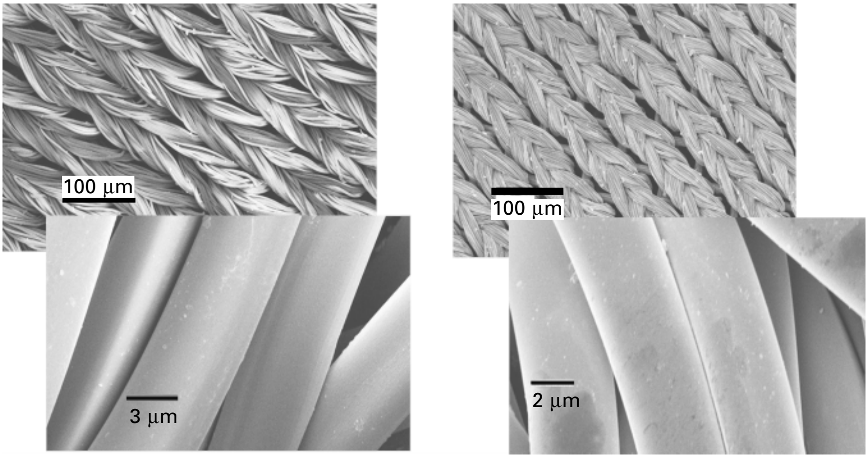
24.5.2 Control of initial resistance

Controlling the initial resistance of the coated textile is important for electronics compatibility and to set the baseline signal for the sensor. Several factors influence the initial resistance of the coated fabric, including the composition and structure (knit) of the base textile, textile pre-treatment, the concentration of monomer/oxidant/dopant used for coating (see Fig. 24.2), polymerisation time and polymerisation temperature, as reported previously (Wu, 2004).


(a)

(b)

24.2 The *in-situ* polymerisation process used to coat nylon lycra strips (2 cm × 25 cm) with polypyrrole. The uncoated strips (a) were stretched horizontally across a wire rack, then stood vertically in the polymerisation solution for coating before being removed for drying and washing (b).



Uncoated nylon lycra fabric
(a)

Conducting polymer-coated nylon lycra fabric
(b)

24.3 Scanning electron microscope (SEM) photographs of uncoated nylon lycra (a) and nylon lycra coated with polypyrrole (b) displaying the uniformity of the polymer coating.

24.5.3 Sensitivity

Sensor sensitivity is another important factor for monitoring joint motion. If highly sensitive, then sensors for wearable biofeedback systems will undergo significant changes in conductivity, that is, have a high gauge factor*, corresponding to a small degree of movement. Conventional silicon and metal strain gauges record gauge factors between 100–170 and 0.3–4, respectively. Gauge factors reported for polypyrrole-coated textiles are of the order of –12 (De Rossi *et al.*, 1999a). The negative gauge factor reflects a decrease in resistance when the textile is strained. By altering the coating procedures and textile substrate, the sensitivity of the sensor can be tuned for different applications. The gauge factors reported to date are adequate for monitoring joint movement within the accuracy limits of a standard goniometer (Gogia *et al.*, 1987) although further research work aims to increase the gauge factor of these sensors to further improve the accuracy of biofeedback during joint motion.

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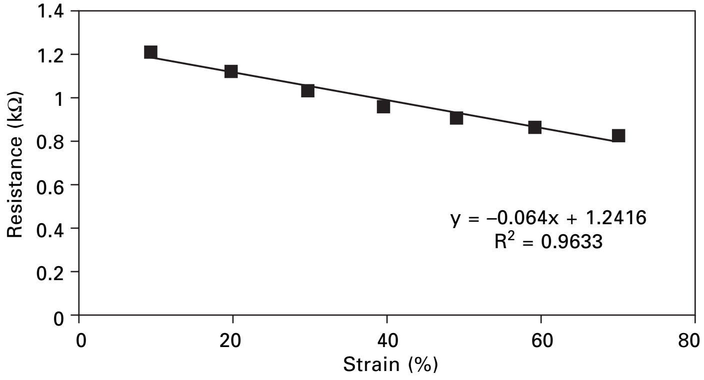
* The gauge factor of the strain gauge is defined as the ratio of the fractional change in resistance to the fractional change in length Cobbold, R. S. C. (1974) In *Biomedical Engineering and Health Systems* (ed., Milsum, J. H.) John Wiley & Sons, New York, USA.

24.5.4 Linear dynamic range

The range over which a strain gauge is linear is vital to ensure repeatability and provide feedback over the required range of joint motion. However, this range is affected by the uniformity of polymer coating across the surface of the textile, textile composition, textile structure and stability of the polymer on the textile. Compared to the limited linear dynamic ranges displayed by other strain gauge types, polypyrrole-coated nylon lycra consistently displays a large linear dynamic range between 10–70% strain, as displayed in Fig. 24.4 (Campbell *et al.*, 2003). The large linear dynamic range displayed by these sensors corresponds to the greatest degree of joint motion required during human motion. However, the sensor must be prestrained a minimum of 10% to ensure joint motion falls within the reported linear range.

24.5.5 Response time

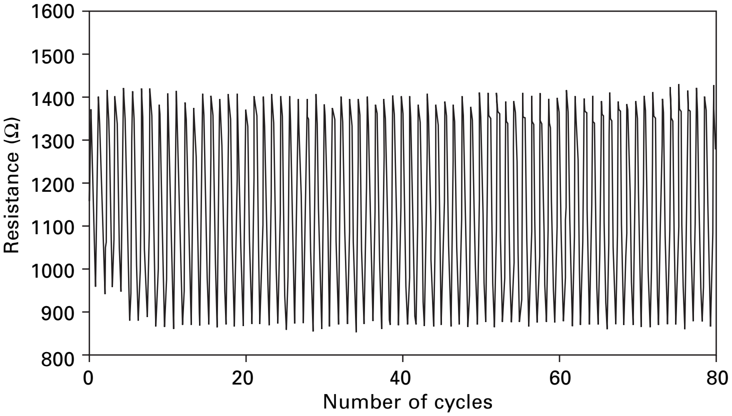
The response time of the textile sensor is required to be as small as possible to ensure an instantaneous response during rapid human movements. De Rossi *et al.* (1999b) noted that polypyrrole-coated lycra fabrics displayed a fast response time when cycled at 1 Hz, which makes them conducive to monitoring human motion. However, this response did not achieve steady state for several minutes (see Section 24.5.7). The response time of the polypyrrole-coated nylon lycra sensors has been shown to be adequate in providing valid and reliable biofeedback during rapid and repetitive human movements such as jumping (Campbell *et al.*, 2003; Munro *et al.*, 2002). The time to steady state did not affect the performance of these sensors under human testing conditions, such that they were proven valid and reliable (see Section 24.9.2).



24.4 The calibration curve of a polypyrrole-coated nylon lycra sensor displaying a large linear dynamic range between 10–70% strain when being cycled at 1 Hz for an average of 15 cycles at each strain value.

24.5.6 Resistive force and hysteresis

An ideal wearable textile strain gauge would exhibit consistently identical and minimal forces on both the stretch and relaxation portions of a cycle, at a given frequency. That is, when dynamically cycling the textiles between varying strain limits, both resistive force and mechanical hysteresis should be minimal. However, similar to other properties discussed previously, the mechanical and electrical hysteresis of the textile sensor are dependent upon textile composition, textile structure (knit) and coating procedures. At commencement of cycling, polypyrrole-coated nylon lycra sensors display an initial decrease in resistive force until they plateau after approximately ten cycles, regardless of frequency. Once the plateau is reached there is no further change in mechanical or electrical properties even after 60 minutes of continuous cycling at 1 Hz as displayed in Fig. 24.5 (De Rossi *et al.*, 1999b, Campbell and Wallace, unpublished data). Therefore, to ensure consistent feedback during human motion, the polypyrrole-coated nylon lycra sensors should be conditioned before use. The force hysteresis generated by the polypyrrole-coated nylon lycra was 0.15 N over the strain range 10–70%. Similarly, the hysteretic electrical response of these sensors approximated 0.02 kΩ (Campbell *et al.*, 2003). It is postulated that these hysteretic effects are due to fibre movement within the textile and the reorganisation of the polymer contacts upon elongation (Campbell and Wallace, unpublished data). Regardless of the cause, the hysteresis responses provide further support for ensuring the sensor is prestrained a minimum of 10% when applied to the supporting garment due to the initial non-linear resistance variation recorded with applied strain (see Section 24.5.4).



24.5 The electrical resistance-time responses of a polypyrrole-coated nylon lycra sensor being cycled between 0–40% at 1 Hz for 80 continuous cycles.

24.5.7 Robustness and environmental effects

The ideal sensor to be used to monitor human motion will be subjected to varying environmental effects and human demands. Consequently, to ensure that the results being received throughout a biofeedback session are not adversely affected by environmental factors, wearable sensors must display minimal mechanical and electrical creep and be stable both on the benchtop and when in use, irrespective of changing environmental conditions. That is, if the textile length or electrical response differs markedly during cycling, feedback could be provided at varying joint angles, negating the effectiveness of the wearable biofeedback system. For polypyrrole-coated nylon lycra there was minimal change in textile length and permanent mechanical textile degradation was recorded only when the textiles were strained beyond their yield point, which varied depending on the amount of lycra within the nylon lycra substrate. With prolonged elongation, the electrical resistance exhibited a slow decline, reflecting electrical creep (De Rossi *et al.*, 1999b). The cause of this creep is multifactorial and, although postulated to be due to the textile substrate, is still under investigation. However, electrical creep did not affect the performance of the Intelligent Knee Sleeve as it is evident only during prolonged elongation and not during fast repetitive movements (see Section 24.9.2). Nonetheless, care must be taken to ascertain the effect of creep and stress relaxation within textiles for other applications, particularly those that may require prolonged sensor elongation.

The difficulty in evaluating many of these factors remains with the stability of the conducting polymer coating under different environmental conditions. Currently, polypyrrole-coated nylon lycra sensors are able to be stored within air-tight plastic bags with minimal change in initial electrical resistance after six months (Campbell and Wallace, unpublished data). In addition, these sensors have been shown to be stable when being used on the Intelligent Knee Sleeve by athletes participating in biofeedback training and being stored in air-tight plastic bags between sessions, provided total usage time is limited to 60 minutes. However, these sensors are still affected by sweat, washing processes and distinct changes in temperature and/or humidity. To overcome these potential limitations whilst the technology is still advancing, disposable sensors, validated for 60 minutes usage time, are currently used in wearable biofeedback systems. However, it is envisaged that with further research, the stability of these sensors for use in the field will improve leading to more robust wearable biofeedback systems.

24.5.8 Compatibility with simple electronics

The simplicity in design and function of these wearable electronic sensors is such that they require minimal power consumption. As the battery is typically the most bulky part of the electronics (see Section 24.6), the associated electronics circuitry to be integrated with these sensors is small and light, facilitating a wearable biofeedback system that can be worn in the field. However, the concept of disposable sensors requires additional functionality within the electronics design and innovative interconnects (see Section 24.7) for operation.

24.6 Functional electronics

Electronics are required to add both power and functionality to wearable biofeedback systems. However, their necessary inclusion in wearable biofeedback systems is problematic, as the battery, electronics boards and feedback modality are rarely flexible and may at times be bulky. In addition, their inclusion, due mainly to the battery, increases the mass of the electronics and may affect the operation of the wearable biofeedback system by affecting the placement of the garment on the joint of interest. Alternative energy sources and flexible motherboards are being investigated in an attempt to make these systems truly wearable (Engin *et al.*, 2005). However, in the current environment, time must be invested when determining the functional specification for a wearable biofeedback device as greater processing or communication requirements typically require greater power supply, greater mass and greater production cost (Engin *et al.*, 2005; Gniotek and Krucinska, 2004). Some important aspects to consider when devising the functional specification for compatible electronics within a wearable biofeedback system have been included in Table 24.2.

24.7 Interconnections

A fundamental component of wearable biofeedback systems is the interconnections between the textile sensor itself and the electronics. That is, the interconnections require optimal pressure and/or good adhesion for optimal conductivity. Interconnections must also be sufficiently robust, a need that is heightened in a system where the sensors are disposable. This problem should be overcome with the use of conductive interconnects that aim to increase the size of the electrode rather than being dependent upon the pressure. However, with movement of the sensor around a joint, the contact between the sensor and the electronics often provides problems as, while they are strong in the shear direction, they are weak in compression and the bending force applied to the sensor encompasses both shear and compression. In addition, conductive fibres are often not able to withstand the constant wearing stresses applied to the biofeedback garment and therefore do not maintain an adequate conductive connection. As inappropriate interconnections can radically affect the performance of the wearable biofeedback system, as well

Table 24.2 An example of some functional specification details for manufacture of electronics components for wearable biofeedback devices

Requirement	Definition/example
Function	What will the system do? System will monitor joint motion during dynamic activity and provide an audible tone when a preset threshold is exceeded. Tone will be audible only within +/– 10% of set threshold.
Features	What features will the system provide for ease of use? System will include one-button push control for self-calibration, sensor replacement alarm, low battery indication and automatic sleep after system has been inactive for two minutes.
Sensor interface	How will the sensor be attached and what are the specifications of the sensor? The sensor part will be easily replaced. The sensor resistance shall be of the order of 10–300 kΩ.
Performance/ calibration	How will the unit operate and under what environmental conditions? For a given use and situation, the angle at which the unit provides the audible tone will be repeatable within 5% over the full environmental and physical operating conditions (10–40 °C; 95% humidity). The unit will be splash proof and self-powered with an operating time of 200 hours. The end-user will be responsible for calibration.
Maintenance	Will the unit be serviceable? No maintenance other than sensor replacement is required; the battery is not replaceable.
Physical/ environmental	What is the manageable size of the unit? The electronics unit will be as small as possible (30 × 30 × 5 mm) and will weigh less than 10 g.
Data handling	What does the unit need to do with the data? No data will be stored within the unit although the unit will be compatible with telemetry devices to transfer data from a field environment to a stationary computer. Future developments of the unit may include data logging, wireless control, collection of multiple signals and processing of information with respect to joint angle.
Cost/quantity/ timing	What is the cost of the system? The system will be designed to be of low cost. The quantity of units and receipt of units can be variable.
Regulatory conform	What regulatory bodies do you need to conform to, what are the conformity procedures and issues and how long will the process take? The unit will conform to the requirements of regulating authorities in countries of interest.

as the ability of the user to easily remove and replace the sensor as required, metal press-studs have been used as they are accepted in clothing products and form a robust interconnection with the electronics. However, in addition to the electronics, they introduce a rigid component into the system and therefore research will continue to alleviate this problem in designing a truly wearable and non-rigid biofeedback system.

24.8 The Intelligent Knee Sleeve: a wearable biofeedback device in action

One example of a wearable biofeedback system using the technology described above is the Intelligent Knee Sleeve*. The Intelligent Knee Sleeve is a lightweight fabric sleeve worn around the knee, which incorporates a disposable polymer-coated textile sensor that is placed over the patella (kneecap; see Fig. 24.6). The textile sensor, integrated into an appropriate electronic circuit (3 V), acts as a textile strain gauge with a wide dynamic range whereby as the sensor is stretched when the wearer bends their knee, resistance within the textile sensor strip changes. At a predetermined threshold resistance based on knee flexion angle, which can be varied, an audible tone is emitted to alert the wearer that the desired knee flexion angle has been achieved. The

24.6 The Intelligent Knee Sleeve. The base sleeve is placed around the knee with the textile sensor placed over the kneecap (patella) and the electronics placed on the side of the sleeve hidden by a fabric pocket. Photo courtesy of CSIRO Textile and Fibre Technology.

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* Wallace GG, Steele J, Innes P, Spinks G, and Zhou D. *Sensors in fabrics with audio feedback: A training tool for enhanced performance and rehabilitation.* International Patent Application WO 03/01 4684, August, 2001.

Intelligent Knee Sleeve is a unique example of a wearable biofeedback system that can provide immediate, individualised, and objective biofeedback to the wearer with respect to knee joint motion during dynamic tasks performed in the field. It therefore increases the objectivity, frequency, and speed of feedback provided to individuals about their landing technique to ensure they are reinforcing the correct technique throughout training sessions. Consequently, the effectiveness of landing training programs is improved, with the aim of reducing the high incidence of non-contact ACL injuries in sports.

24.9 Why is the Intelligent Knee Sleeve needed?

The human knee joint has a high susceptibility to injury due to its incongruent structure and the high forces imposed on the joint, particularly during dynamic activities such as landing. Of all the knee ligaments, the anterior cruciate ligament (ACL), one of two ligaments crossing within the knee joint, is the most frequently injured (Johnson, 1983). When the native ACL is ruptured, the knee joint is predisposed to episodes of giving way, further risk of damage to the cartilage discs within the knee joint, loss of proprioception via damage to mechanoreceptors in the joint and ligament itself, recurrent pain, and likely degeneration of the knee joint because of excessive laxity and persistent instability (Acierno *et al.*, 1995). Although ACL reconstructive surgery can be a viable treatment option, it is preferable to prevent these potentially debilitating non-contact ACL injuries from happening in the first place, as ACL reconstruction often results in losses in joint range of motion, muscle strength, and control (Draper, 1990). As nearly one-quarter of non-contact ACL ruptures are caused by poor landing technique (Noyes *et al.*, 1983), a device such as the Intelligent Knee Sleeve, designed to assist in teaching correct landing technique, is urgently required.

Most non-contact ACL injuries occur when landing from a jump with the knee flexed less than 30° (Cochrane *et al.*, 2001). When landing using this extended knee posture, contraction of the quadriceps muscles on the anterior thigh, which are activated to prevent the lower limb from 'collapsing', unfortunately also increases ACL strain (Torzilli *et al.*, 1994; Draganich and Vahey, 1990). Furthermore, with the knee extended, the hamstring muscles, on the posterior thigh, are inefficient in providing sufficient posterior tibial draw to counteract the quadriceps-induced anterior tibial translation, due to their inefficient line of action (Pandy and Shelbourne, 1997). For this reason, it is strongly advocated that individuals should bend their knees when landing to enable the hamstring muscles to more effectively protect against high ACL strain (Cochrane *et al.*, 2001). Flexing the knees throughout the landing action can also 'cushion' the forces generated at foot-ground contact, thereby reducing the jarring effects of landing, as well as lower an individual's centre of gravity, in turn, enhancing their stability (Steele and

Milburn, 1987a,b). Therefore, to reduce the potential for non-contact ACL injury, it is advocated that individuals should land with a relatively high knee flexion angle combined with a large range or amplitude of joint motion over which to dissipate the energy in muscles (Mizrahi and Susak, 1982a,b; Cochrane *et al.*, 2001).

The benefits of landing programs in reducing ACL injuries are readily acknowledged by the implementation of landing training programs in sports such as Australian Rules Football (Seward *et al.*, 1999), soccer, volleyball, and basketball (Hewett *et al.*, 1996, 1999; Caraffa *et al.*, 1996). However, participants in such programs currently have no method to ensure they are bending their knees sufficiently during training. That is, no field-based method currently exists that can provide immediate feedback to individuals with respect to knee flexion angle during dynamic landing tasks. Therefore, a wearable joint biofeedback device, such as the Intelligent Knee Sleeve, fills this current void.

24.9.1 Proof of concept: feasibility of using the Intelligent Knee Sleeve in the field

To establish whether using the Intelligent Knee Sleeve as an instantaneous biofeedback device to teach correct landing mechanics was feasible, members of an elite Australian Rules football team completed three standard landing training sessions per week using the device to assist them to bend their knees appropriately when performing landing movements. The results of this field-based feasibility study were positive in that the base sleeve was found to be comfortable, remaining in the same position on the lower limb with the sensor over the kneecap during performance of all activities, and the feedback challenged the players during performance of landing activities. Furthermore, although minimal time was available to educate the players on independent use of the sleeve, the sleeve users had little difficulty in learning its correct operation and welcomed the biofeedback device and training program as they were novel, challenging and informative.

24.9.2 The Intelligent Knee Sleeve: how valid and reliable is the audio feedback?

Although proven to be a feasible biofeedback device, it is imperative to establish validity and reproducibility of the feedback provided by the device if it is to be effective in improving the user's landing technique. To establish validity and reliability of the Intelligent Knee Sleeve, 12 subjects (mean age 26.1 ± 3.2 years) involved in sports requiring landing movements and with no history of knee joint disease or trauma performed ten trials of four landing movements while wearing the Intelligent Knee Sleeve on their dominant limb. The audible feedback tone was set to be emitted at two programmed knee flexion angles during the four movements, which included: a shallow hop (25° of knee flexion); a deep hop (45°); a 30 cm step down (45°); and a 30 cm step down followed by a rebound movement (45°). The total time to collect the data per subject replicated the typical time of a landing training session (30 minutes). The two knee flexion angles at which the audible tone was emitted were programmed manually using a goniometer and goniometric measurements reconfirmed the knee angle at which the audible tone was emitted at the completion of all trials of each movement.

During the trials each subject's landing action was characterised by collecting the ground reaction forces generated at landing using a force platform (1000 Hz) and monitoring their motion using an optoelectronic motion analysis system (200 Hz). Data from the knee sleeve were also sampled (1000 Hz) to determine the onset of the audible tone. Paired *t*-tests revealed that the knee sleeve was valid, in that the programmed angle (set using a goniometer) was equal to the angle at which the audible feedback tone was actually emitted (calculated using the motion analysis system). The knee sleeve audible tone also proved to be highly reliable with intra-class correlations calculated from the knee angle at audio onset ranging from $R_1 = 0.903$ to 0.988. Based on these results, the knee sleeve was deemed to be a valid and reliable device to provide information about knee flexion angle during dynamic landing movements.

24.9.3 Does feedback provided by the Intelligent Knee Sleeve improve knee flexion during landing?

To ascertain whether the biofeedback provided by the Intelligent Knee Sleeve was effective in assisting athletes to learn to flex their knees more during dynamic landing movements, a pilot trial was completed involving 37 subjects (mean age 23.6 ± 4.0 years), all of whom were involved in sports requiring landings and who had no history of knee joint disease or trauma. Each subject performed a series of landing movements, whereby they landed on their dominant limb with their foot centrally located on a force platform whilst catching a football, before and after a six-week training program. During each testing session ground reaction force data were collected (1000 Hz) using a force platform whilst kinematic data characterising landing technique were collected (200 Hz) using an optoelectronic motion analysis system. At the completion of initial testing, subjects, matched for age, height, body mass, injury history and playing ability, were divided into three groups:

1. subjects who participated in a landing training program and who received audible feedback from the Intelligent Knee Sleeve during this training – 'knee sleeve trained';

2. subjects who participated in a landing training program wearing the Intelligent Knee Sleeve but without receiving any audible feedback during training – 'placebo trained'
3. subjects who did not participate in the landing training program – 'control'.

Subjects in the knee-sleeve-trained and placebo-trained groups then participated in a six-week landing training program to learn correct landing mechanics, completing three 30 minute training sessions per week.

When comparing each subject's landing technique displayed pre- and post-training, it was noted that the control and placebo trained groups displayed, on average, less knee flexion, as evidenced by percentage change data, during the post-intervention session at the time of initial foot ground contact during landing (control = –11%; placebo = –23%); at the time of the peak resultant force (control = –8%; placebo = –4%) and the maximum knee flexion angle (control = –4%; placebo = –6%). In contrast, the knee-sleeve-trained subjects displayed the desired increases in knee flexion post-intervention at initial foot-ground contact (+14%), peak resultant force (+1%) and maximum knee flexion angle (+7%). In fact, although not statistically significant, the increase in maximum knee flexion angle from pre- to post-intervention displayed by the knee-sleeve-trained group was on average 8°, an increase that could be considered functionally relevant. Interestingly, although both the placebo and knee-sleeve-trained groups participated in the same intensive six-week landing training program, only those subjects who received immediate feedback from the Intelligent Knee Sleeve during training achieved positive changes in their knee flexion angle. As the subject numbers and statistical power in this pilot investigation were low, further investigation is warranted to confirm the trends displayed in the present investigation whereby participating in a landing training program using the Intelligent Knee Sleeve to provide audible feedback with respect to knee flexion angle assisted in teaching athletes to bend their knees more during landing after decelerating abruptly when catching a ball (Munro and Steele, 2005).

24.9.4 The Intelligent Knee Sleeve as a rehabilitation tool

Apart from the landing training application described previously in this chapter, the Intelligent Knee Sleeve can also be incorporated into rehabilitation programs to ensure patients perform their rehabilitation exercises properly, moving their limbs through the desired range of motion. For example, the Intelligent Knee Sleeve system can be used to assist patients in rehabilitation following ACL reconstructive surgery. Following arthroscopic surgical reconstruction of the injured ACL, most patients, particularly those who are involved in running or jumping sports, notice an asymmetric loss of knee flexion and extension (Millett *et al.*, 2001). Therefore, the primary goals of postoperative

ACL reconstructive surgery are to regain full knee range of motion and to recover muscle strength and control (Draper, 1990) with this re-education process usually taking between four to seven months of physiotherapy. The Intelligent Knee Sleeve can assist ACL reconstructed patients to learn how to move their knee through a desirable range of motion throughout typical rehabilitation exercises and, in turn, promote the recovery of knee range of motion and function. The Intelligent Knee Sleeve may therefore increase the effectiveness of rehabilitation for ACL reconstructed patients, perhaps simultaneously promoting the recovery of knee muscle strength and neuromuscular control. Furthermore, when coupled with data logging capabilities, the Intelligent Knee Sleeve would provide the ability to evaluate rehabilitation routines, providing new knowledge to rehabilitation specialists on the effectiveness of these routines.

Trials are currently in progress to determine the efficacy of the Intelligent Knee Sleeve as a biofeedback device in enhancing post-knee-replacement surgery rehabilitation. As it is suitable for use by people of a wide age range, both independently and supervised at home or in the clinic, and on most joints of the human body, wearable biofeedback systems have a great many applications in a broad spectrum of activities, ranging from technique training to enhanced performance or for injury prevention as well as technique monitoring during rehabilitation.

24.10 Other applications of wearable biofeedback technology

Wearable biofeedback systems that monitor joint motion have broad application and can be used to provide immediate feedback pertaining to movement of most major segments of the human body. For example, placing sensors on a glove may be able to improve a golfer’s putting technique, and thereby handicap, by providing feedback when there is excessive wrist motion which may detract from an optimal performance. However, regardless of the application, care is required to ensure the base garment does not provide support for the joint, is comfortable for the wearer and remains in the same position on the limb to ensure reliability in the feedback being received. Therefore, the base garment provides additional challenges to the designers of wearable technology, particularly those that provide biofeedback to the user during human motion.

24.11 Future directions

As wearable sensing technologies reach the prototype stage and undergo field trials there is no doubt that the need for specific improvements will be identified. However, even now it is obvious that parallel developments in the following areas will facilitate the emergence of new wearable technologies to monitor human motion.

24.11.1 Integration of electronic materials into textiles

Recent studies have shown that some electronic polymers (sulfonated polyanilines) act as highly effective dye molecules (Wu, 2004) being readily incorporated into host textiles of differing composition and structure and imparting electronic properties with no effect on textile handle. Undoubtedly future studies will result in the synthesis of improved (higher conductivity) electronic polymers tailored to match textile substrates at the molecular level.

24.11.2 Electronic fibres

An alternative to the dying approach to impart electronic properties is to weave electronic fibres through host textile structures. At present, there are only limited fibres, predominantly based on the organic conductor polyaniline, with handle akin to wearable textiles. Pomfret *et al.* (1998) have achieved conductivities in excess of 1,000 Scm^{-1} with a Young's modulus in the order of 40 MPa for fibres wet spun from a solution of polyaniline and therefore improvements to impart these electronic properties to fibres continue to be made in laboratories around the world.

24.11.3 Novel power sources and storage devices

The power sources and storage devices we currently utilise were not conceived, designed or fabricated with wearable systems in mind. While in the short term, off-the-shelf components will be used, truly wearable energy conversion and storage devices deserve a revolution in thought. The need, at least, is being recognised with projects in wearable solar energy conversion (www.natick.army.mil) and wearable batteries (www.uow.edu.au/science/research/ipri/innovations.html), such as polymer-based fibre batteries (Wang *et al.*, 2005), being initiated.

24.11.4 Electronics and interconnects

It is also true that the evolution of conventional electronics was not influenced by the 'wearables' community. However, continued miniaturisation may make electronics so unobtrusive that the lack of natural compatibility disappears as a major issue or concern. While miniaturisation may well provide seamless integration and compatibility, it will undoubtedly exacerbate the need for more innovative and effective interconnection systems to the outside world. Even now, when using conventional electronics, the interconnection between the soft(er) world of textiles and the hard(er) world of electronics is a challenge. Innovative approaches, undoubtedly involving new intermediaries and new 'contact materials', are required.

24.11.5 Biomechanical applications

Research leading to the development of robust wearable systems that operate independently of the environment, are machine washable, sweat resistant and, in some cases, biocompatible, is required. Furthermore, improved data processing, downloading and information transfer capabilities from multiple sensors are needed to ensure wearable biofeedback systems can withstand the rigours of physical activity, under all dynamic conditions likely to be encountered in activities of daily living, work, and recreation.

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25

Applications for woven electrical fabrics

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25.1 Smart fabric technologies

25.1.1 What is a smart fabric?

In the absence thus far of any established taxonomy, this section will seek a framework of definitions and categories, to better understand and classify the member technologies. Firstly, where can a distinction be drawn between technical fabrics and smart fabrics? For example, do smart fabrics as a class include the many proprietary fabrics that use a laminated polytetrafluoroethylene (PTFE) membrane to render them waterproof yet breathable? Subjectively, instinct is to exclude such breathable textiles, but the reasoning is not immediately explicit. They seem to be clever, but not necessarily 'smart'.

The Larousse technical dictionary defines smart or intelligent materials as those that 'respond to an external stimulus in a specific, controlled way', listing as exemplars photochromic, piezoelectric and liquid crystal materials. To create a definition it is possible to borrow a key concept here, of a material that responds to a stimulus. To put it another way, the material has a number of distinct states, with differing physical properties in these states. Furthermore, the material will transition repeatedly between these states with a given external stimulus.

In the case of a photochromic material, such as the coatings used in light-reactive sunglasses, the stimulus is light energy and the physical states are high and low transparency (or strictly, polarisation angle of transmitted light). A liquid crystal material, of the type that composes laptop computer screens, also moves between high and low transparency, but the stimulus is electrical energy. In a piezoelectric material used, for example, to generate the alarm bleeps of a digital wristwatch, the stimulus is again electrical current, and the states are an expansion and contraction of the material. It is this vibration that causes the bleeping. By this borrowed distinction, then, the breathable waterproof PTFE membrane fabric is not a smart fabric. It may appear at first inspection to behave in two distinct manners, remaining permeable when presented with water in vapour form, whilst forming an impenetrable barrier to liquid water. However, the fabric itself always occupies the same state.

The microscopic pores in the PTFE membrane remain the same whether presented with liquid water droplets, which are simply too large to pass through the pores, or water vapour, in which the water molecules are separate and thus small enough to pass through. It is the water molecules that behave differently according to their physical state, rather than the fabric exhibiting any change. In contrast, a smart fabric might actually alter the size of its pores, and thus occupy distinct high and low states for its permeability or thermal insulation. The external stimulus might be humidity, temperature or even a controlling electrical current. This latter point illustrates a further useful subdivision within smart fabrics, which is explored in the following section.

25.2 Active and passive smart fabrics

Consider the stimulus that might spur a variable-pore-size fabric into action. A fabric that responds to either humidity or temperature as a stimulus would have what can be termed a passive response. The fabric would react and undergo its state change according directly to some environmental factor. The earlier example of photochromic coatings used in light-reactive sunglasses is another case of a passive smart material.

Hopefully, the state change proves useful, in both manner and direction of change. In this example case, a rise in humidity or temperature would advantageously trigger an increase in pore size. This in turn should serve to better ventilate the fabric or lessen the warmth afforded by it. This manner and direction of state change would thus perform a useful homeostatic function. There would be no need for intervention or control, and the smart fabric would quietly and automatically go about its work, attempting to regulate the humidity or temperature within a garment, for instance. Incidentally, the physical mechanism through which this might be accomplished could be some hygroscopic (moisture absorbing) polymer or a shape memory material. It is possible to imagine a woven or knitted fabric structure that alternately tightens or loosens, as its constituent hygroscopic or shape memory yarns change shape.

The alternative to a passive smart fabric is an active one. Both terms are borrowed from electrical engineering, where ‘active’ is used to denote a device where there is an input of energy. By implication, this required energy input is used to control or drive the device, and in the vast majority of cases this energy input is electrical. The archetypical active and passive devices in electronic engineering are filters. Whilst a passive filter can only ever reduce unwanted frequencies, an active filter uses an amplifier to add further energy, and can instead boost the desired frequencies. Turning once more to the example smart fabric with the variable pores, the required stimulus might be an input of electrical energy. An electric current might serve, say, to heat a shape memory metallic yarn to a transition temperature that effects its change in dimension. This variant of the fabric would thus show an active response.

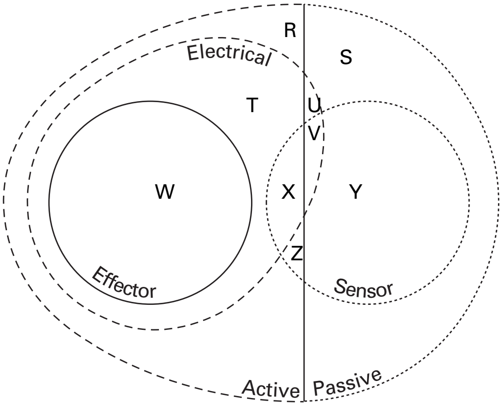
As noted earlier, the vast majority of active smart fabrics tend to be electrical in nature. Whilst this is not in itself a definitive feature, electrical current is usually the most convenient means of imparting an energy input, and one which can be very competently manipulated. One notable exception is the use of light in fibre-optic based fabrics, which can be active, but not electrical. Whilst 'electrical' or 'conductive' smart fabrics might easily constitute their own subdivision within another taxonomy, it is important to note that they are not interchangeable with 'active' smart fabrics as a category. Similarly, passive smart fabrics usually appear to rely upon chemistry or physics, rather than electrical effects. Once again, however, this correlation is neither absolute nor definitive.

25.2.1 Sensor and effector smart fabrics

Another useful distinction within smart fabrics is whether they are used as sensors or effectors. Both are electrical engineering definitions for types of transducer. Transducers convert some physical variable into an electrical signal, or vice versa. Sensors are used in one direction, converting a variable such as light, sound or temperature into an electrical signal. Effectors are used in the other direction, converting electrical energy into some physical manifestation.

Piezoelectric materials are also very commonly used as both sensors and effectors, sometimes simultaneously. In medical ultrasound machines, a piezoelectric crystal generates pulses of ultrasound, the reflections from which are sensed an instant later by the same crystal, working alternately as effector and sensor. Note that this arrangement can also be termed 'active' sensing, as energy is introduced by the pulse into the sensed medium. Effectors, by definition, are active. An input of electrical current is required for conversion into another form of energy. Sensors can be both passive and active. Note the parallels between this and the 'pulse-echo' system for medical ultrasound, above.

In the passive smart fabrics of the previous section, the sensing and effecting tend to be intrinsically coupled together. Our aforementioned variable porosity fabric can be seen to both sense and react simultaneously – the change of state that accompanies a stimulus is the same change of state that effects the variation in pore size. The same is true in photochromic sunglasses, where the response to sensed light and the desired effected change are one and the same. The taxonomy is illustrated in Fig. 25.1. Table 25.1 summarises the relevant regions R to Z of our informal taxonomy. Intelligent Textiles Limited weave electrical smart fabrics, regions T to X, which will be discussed in the following sections.



25.1 Taxonomy.

Table 25.1 Summarises the relevant regions R to Z of our informal taxonomy

Region	Description	Examples
R	Active, non-electrical, non-transducer	
S	Passive, non-electrical, non-transducer	Thermal phase-change materials (PCMs); photochromic fabrics
T	Active, electrical, non-transducer	Computational fabrics; photovoltaic fabrics; thermoelectric generator fabrics
U	Passive, electrical, non-transducer	Resistor, capacitor, inductor components; power and communication backplanes
V	Passive electrical sensor	Mechanical switch and keypad fabrics; pressure sensitive fabrics (some); capacitive sensor fabrics (some); temperature measurement fabrics; light sensitive fabrics
W	Active electrical effector	Heating fabrics; electroluminescent and LED illuminating and display fabrics; Peltier thermoelectric fabrics
X	Active electrical sensor	Pressure-sensitive fabrics (some); 2D and 3D positional pressure-sensitive fabrics; capacitive sensor fabrics (some)
Y	Passive, non-electrical sensor	Chemical indicator fabrics (thermochromic, moisture, acidity)
Z	Active, non-electrical sensor	Fibre-optic strain measurement fabrics

25.3 Electrical smart fabrics

25.3.1 Woven electrical fabrics at Intelligent Textiles Limited

Intelligent Textiles Limited has operated a woven electrical fabrics program since 1998. From the platform of the earliest technology, a pressure sensitive fabric named Detect™, they have since developed a versatile toolkit of raw materials, weave structures and circuit components from which they can fabricate a broad range of electrical smart fabrics. These fabrics can be variously active, passive, sensing and effecting in their function. Using this toolkit, it is possible to construct fabrics that incorporate multiple conductive yarns, introduced during the weaving process and integral to the very structure of the cloth. These conductors are mutually interconnected in a fashion that is controlled by the woven structure. Instead of weaving checked or tartan patterns in different coloured yarns, colours can be swapped for conductors to weave electrical circuits.

The elemental circuit components that can be fabricated at present are all passive, namely resistors, capacitors and inductors, plus some electromechanical structures such as switches. Note that the term ‘passive’ is used here in the specific sense of denoting electrical components that have no ability to amplify a signal, and by that implication, contain no semiconductor material (or strictly, no transistors). The resistor, capacitor and inductor components are themselves composed of tightly dimensioned geometric networks of conductive elements. Each element is a segment of a conductive yarn. At their simplest, networks can comprise a handful of such elements, or use recursive and combinatorial structures to quickly rise into thousands of elements. The woven conductive structures also provide the equivalent of conductive tracks, as found on conventional printed circuit boards (PCBs). Thus, multiple components can be positioned arbitrarily within a given piece of fabric, and route signals and power between them. Effectively, hard PCBs can be translated into pliable woven fabric. In fact, given a sufficiently large area of fabric, entire circuits of resistors, capacitors and inductors can be fabricated. That said, the density of components is dramatically less than conventional circuit boards, and all but the simplest circuits can demand many metres of fabric.

Fortunately, many useful electrical devices are very simple circuits, or even single components of a particular design. For instance, a large variety of conventional sensors are based upon little more than single resistors, whose construction and composition are so chosen as to respond to a stimulus with a change in resistance. Light, temperature and mechanical strain are all routinely measured with such specialised resistors, although sound transducers tend to be inductive or capacitive in nature.

It is interesting to compare the fabrication scale and density of these woven electrical components against the historical development of mainstream electronics. The original electrical pioneers machined large parts in glass and metal in order to make their seminal electrical components. In the 1960s and 1970s, machined metal and blown glass gave way to plastic packages and etched semiconductor materials. Components shrank, from centimetres in length, to millimetres, to the current micro- and nanometre scales

The change in medium from wafers of semiconductor to woven fabric, signals a return to the centimetre- and millimetre-sized components of the early pioneers. Similarly, the complexity and functionality of the resulting woven components has regressed to electrical first principles, but reapplying these first principles to a new fabrication medium is a fertile area of development.

25.3.2 Passive, non-transducer fabrics

As introduced in the preceding subsection, the most basic electrical devices that can be constructed as woven textiles are passive components – resistors, capacitors and inductors. Although these basic components all find application in various guises as sensors and effectors, they can also conceivably be used purely as components within larger circuits, and not necessarily as transducers. It is entirely possible, for instance, for a piece of fabric with these components to constitute a complete passive audio filter circuit.

Resistors of specific value can be fabricated in arbitrary shapes and sizes within a stretch of fabric. A resistor's value is generally independent of the area of fabric it covers, which is achieved by using large networks of parallel and series conductive elements. The resistors' parallel nature means they possess great redundancy, and so their function and value is fault tolerant, degrading gracefully if the fabric is partially damaged. The resistance values can range from a few ohms to many megohms, and when manufactured on automated power looms their tolerance on desired resistance is typically within 5%.

The area of a resistor is usually only a few square centimetres for signal wattages. For greater power dissipation, the resistor can be scaled up in area. Every square metre of fabric will comfortably dissipate several hundred watts of power. The configuration of the fabric resistor, as a very thin, broad sheet, is ideal for efficient heat dissipation. This efficiency at dissipating heat is one factor that makes the fabric resistor particularly useful as a heating element. This is a mode of use which constitutes an active effector, rather than a passive component.

The same is true of the capacitor and inductor components that can be fabricated with the same techniques. They both find applications as various types of sensor and effector, but when one considers them not as transducers but as replacements for conventional PCB mounted devices, they are dreadfully cumbersome and costly. Again, these two remaining types of passive component can be embodied as networks of contiguous conductive elements within the fabric structure. Unlike resistors, however, the construction of capacitors and inductors relies to a greater extent upon the specific geometry of the conductive elements. By forming the elements into various loops, spirals and meanders within the fabric, it is possible to duplicate some of the geometric features of conventional capacitive and inductive devices. However, attaining specific values, from within an adequately broad range, is far more problematic than for woven resistors.

Another passive, electrical and non-transducer application for these woven fabrics is to provide wiring looms or circuit backplanes for conventional electrical. For example, a conductive fabric backplane might incorporate the 'wiring' for distributing power or audio signals between a number of portable devices worn upon the body. Telephones, music players, computers and their requisite headphones and microphones may all be interconnected in this manner, in an arrangement termed the personal area network, or PAN. Another attractive prospect is to consolidate and centralise the power supplies for these devices, reducing weight. A similar application lies in utilising the textile upholstery in vehicle interiors to additionally replace the conventional wiring looms. The conductors in a fabric wiring loom can even be designed to terminate in broadened areas for use as electrodes, when incorporated into garments for biomonitoring.

25.3.3 Passive sensor fabrics

As mentioned earlier, many common sensor types are based upon little more than a single resistor, whose arrangement and chemical composition are so chosen as to change the resistance according to a stimulus. Given that it is possible to produce resistor components with the woven technique toolkit, a number of these sensors can be translated into fabric. One physical variable that is routinely measured in this way is temperature. Thermistors are specialised resistors, usually based on semiconductor materials, that show a pronounced 'resistance temperature coefficient', or change in value according to temperature.

Alternatively, pure metallic conductors are often used, in which case the resistors in question are often named 'resistance temperature devices', or RTDs. The resistance temperature coefficient of pure metals is much smaller than that of the semiconductors developed specifically for use in thermistors, but is still adequate for reliable measurement when metallic yarns are used. Making RTD measurements from the fabric resistors described here can typically be achieved with around 5% accuracy, within the operating temperature range of the fabric. Advantageously, the same resistor that might constitute a fabric heating element can also be used as the sensor for the resistance temperature measurement. The fabric resistor alternates between effector and sensor, much like a piezoelectric ultrasound probe. Other physical variables that can be sensed with these passive resistors, in various configurations, include moisture, galvanic skin resistance and mechanical strain.

Conventional capacitive and inductive sensors are primarily applied to non-contact proximity detection. That is, determining the distance of nearby objects via their disturbance of a capacitor or inductor's electrostatic or electromagnetic field, respectively. Fabric capacitors and inductors can be used in this manner, albeit currently with greatly reduced acuity than their conventional counterparts. It has proved possible, at least, to perform 'event detection', in which the sensor is not required to measure the distance of an object, but merely that it is present nearby or absent.

A wholly different approach can also be taken for sensing using electrical fabrics. The fabric 'Detect'™, by Intelligent Textiles Limited, can sense physical contact or pressure. The sensing is achieved with millimetre-sized, mechanical switches in a regular array across the surface of the fabric. The switches are created by controlling the local weave structures around the conductive yarns. A 10 cm square piece of fabric, say, may typically comprise several hundred such electrical switches. It may help to imagine a very broad computer keyboard, with hundreds of keys, miniaturised and flattened into fabric form. Detect is a second-generation technology, which offers touch sensitivity in a single, conventionally woven sheet. To all other practical intents, including magnitude of manufacturing costs, Detect is an ordinary piece of fabric. It can also be cut, sewn and handled in a conventional manner.

The fabric can be used in both active and passive modes. When used in a passive sensor fashion, as a simple switch, Detect can replace a variety of input devices such as pushbuttons, keypads, limit switches and keyboards. Its function is that of a momentary contact, normally open push button. Because it is a mechanical switch, with real moving contacts, Detect is a direct replacement for conventional pushbuttons, keys and microswitches. It requires no additional signal conditioning or processing, beyond the debouncing that might be afforded any conventional switch, which is a prime advantage of its passive nature. Detect fabric is designed and manufactured bespoke, to suit a specific application, some of the general specifications that can be achieved are as follows. Operating pressure for the switches can be as low as approximately 5 kiloPascals, but a pressure of around 50 kiloPascals is more typically used in switchgear applications, which is a comfortable, light force to apply with a fingertip. Operating pressure can be predetermined at time of manufacture.

The minimum pitch of the switches is approximately 2 mm by 5 mm, although 2.5 mm is often used for compatibility with conventional electrical components, connectors and PCBs. This results in a possible switch density of over 100,000 switches per square metre, which overcapacity is often used to introduce redundancy and improve robustness. The switches' open circuit resistance has been measured at over 40 MΩ, as befits a switch with genuine mechanical separation between contacts. The closed circuit resistance varies according to specific design, but it is most cost-efficient to limit this specification to around 1 kΩ, if acceptable. Operational lifespan of the switches is typically in excess of 1,000,000 operations, and the abrasion resistance of the fabric is similarly good, perhaps surprisingly so. According to the nature of the base fibre and the fabric weight, the Martindale abrasion resistance has variously been measured at between 20,000 and 40,000 cycles.

Detect is routinely woven with base fibres of cotton, polyester, wool and nylon, whilst a typical finished weight is *circa* 250 grams per square metre. Obviously, the base fibre also affects fabric washability. Woollen base fibres, whilst very resistant to abrasion and affording excellent elastic recovery, suffer poor washability. A Detect fabric woven from polyester base yarns, conversely, can be reliably washed over 30 times on a 40 °C cycle.

25.3.4 Active sensor fabrics

In addition to using Detect as a passive switch, it can also be used as an active sensor. This can be achieved by energising the switch array with a low reference voltage, and then making an analogue measurement from one set of switch contacts. Comparing the analogue sensed voltage with the reference voltage then allows more information to be gleaned from the fabric about the nature of the physical contact. In one fabric configuration, this analogue measure can be used to determine the location of a physical contact. This can be a one-dimensional measurement, whereby the fabric senses a single distance measurement between the point of contact and another fixed point. This configuration proves useful for emulating slider-style controls or keys arranged on a continuum, like piano keys.

If the same switch configuration and measurement are duplicated twice within a piece of fabric, ideally measuring one horizontal and one vertical distance, the fabric can be interrogated for an absolute two-dimensional position. This same measurement system is used in resistive touchscreens for palmtop computers. The fabric can also take relative measurements, with a small alteration in interface software, which is then analogous to the tracker pads found on many laptop computers. Whether the distance measurements are treated as continuous, as in touchscreen and tracker pad styles of interaction, or the measurements are thresholded and quantised to provide an array of discrete keys or buttons, this two-dimensional positional technique finds a great many useful applications.

The primary advantage of these analogue techniques is their reduction in interconnections compared to the simple passive switch sensing described earlier. Taking the example of implementing a qwerty keyboard with perhaps one hundred keys, for instance, a two-dimensional positional sensing fabric will require only two analogue signal lines, plus two energising inputs. This means that only four signal tracks need be routed through the fabric, and the off-fabric connector remains small, inexpensive and unobtrusive. Conversely, treating each key as a separate passive switch would require over one hundred signal lines, one for each key. Even treating the keyboard as a row-column multiplexed matrix, a standard keyboard technique, would require some twenty signal lines.

The major disadvantage of the analogue technique is its requirement for fairly complex interface circuitry. Not only must this circuitry comprise analogue-to-digital conversion (ADC) hardware and the microprocessor means to interpret the results, but also the signal conditioning, shielding and filtering to remove the noise that inevitably affects analogue systems. Pragmatically, each application case must be assessed on its own merits, and the best compromise solution selected. There is, at least, a spectrum of solutions of increasing complexity from which to select. Using similar interface circuitry, but altering the fabric configuration slightly, allows Detect to sense the area of a contact, rather than its position. Again, an analogue measurement is taken, but in this case it is proportional to the number of switches within the array that are closed. Simultaneously taking more than one such area measurement allows a picture to be composed of the shape of a contacted area. With sufficient separate measurements, a pixel by pixel pressure map can even be determined. These techniques are particularly useful in upholstery applications, for monitoring posture or classifying the seat occupant, the latter to better inform airbag deployment in cars.

Rather than making many area measurements separated in space, a different monitoring system can alternatively make many area measurements separated through time, from a single transducer. Inspecting the manner in which an area of contact changes through time can provide information about the velocity, impulse and dynamic pressure of a contact or impact. The Detect fabric, then, demonstrates great versatility as a contacting sensor device, with a variety of fabric configurations and a variety of means for interrogating these sensors. For non-contacting sensing with fabrics, the capacitive and inductive sensors described in the previous subsection provide a possible solution. These types of sensors are most often used in an active fashion, energised with an alternating current to establish their electrical fields.

25.3.5 Effector fabrics

By far the simplest electrical effector fabric is the resistance heating element. Any conductive material that carries an electrical current will generate heat, usually as an unwanted and inefficient by-product. The resistance heating element, such as those in electric kettles and ovens, makes virtue of this phenomenon, and is the only 100% efficient effector. In previous sections, the use of woven resistor components has been discussed, including their ability to be repeatedly fabricated to an arbitrary resistance value, size and shape, as well as their efficiency at dissipating heat. All of these factors result in woven electrical fabrics being excellent in flexible heating applications. In fact, Intelligent Textiles Limited manufacture a specific format of low-voltage woven heater under the name 'Heat'™ fabric. Like Detect, Heat fabric appears to be an ordinary woven fabric. It is thin, flexible, drapeable and breathable. It can be cut and sewn in a similar manner to conventional fabrics, so is easy to incorporate into the manufacturing of apparel or soft furnishings.

The base material for Heat fabric can again be chosen from cotton, polyester or wool, with typical fabric weight around 250 grams per square metre. Composition affects washability, once more. Heat fabric can be designed to survive upwards of 30 washes, but in many of the common upholstery applications, this is not a requirement. Upholstery weight Heat fabric, with a coarse micron woollen base fibre, is less washable but has excellent abrasion qualities. Martindale results for Heat are generally superior to Detect, and woollen Heat variants have achieved over 100,000 cycles.

Turning to Heat fabric's electrical specifications, elements can be manufactured to within 5% of a specific resistance, within the range of five ohms to perhaps a megohm. Heat fabric can comfortably dissipate over 100 watts per square metre (named the fabric's 'energy density'), up to an operating temperature of around 100 °C. The flexibility in specifying a resistance for the heating element gives great freedom to design a heating system of a given wattage, working at a particular voltage. This becomes very useful in battery-powered portable applications where, for example, a battery can be selected on grounds of its capacity or package size, rather than its rated voltage. A further advantage of Heat fabric is its ability to provide a non-homogeneous distribution of heat output across its surface. That is, the combination of resistive elements and wiring loom within the same fabric allows us to place heaters wherever they are most effective or efficient within that piece of fabric. For example, one component produced is for a heated glove lining, where power is conducted from a wrist mounted battery to heating elements in each fingertip. This serves to minimise wasted power, concentrating the heat distribution where it is needed most. Again, this factor is particularly relevant in battery-powered applications, where energy capacity is the bounding factor for these products' effectiveness.

It seems usually to be a surprise outside of electrical circles just how power-hungry electrical heating can be, compared to the majority of electrical applications. Whilst a digital watch might consume only microwatts, and talking on a mobile phone perhaps some few hundred milliwatts, perhaps five or ten watts is consumed just to heat the fingertips to any significant degree. This means that battery-powered heated products usually suffer from large or expensive batteries, short lifespan or low heat output, or perhaps all four at once. It is particularly useful, then, that Heat fabric can also be used as a temperature sensor, as described earlier as a passive sensor property. A product that can monitor and regulate its own temperature, effecting climate control, can prevent excessive heating and thus further conserve energy. Heat fabric constitutes the largest proportion of Intelligent Textiles Limited's work into effector fabrics, not least because the marketplace for flexible heating is relatively mature, and the technology is straightforward and easily appreciated by the consumer. Despite this, the techniques involved in creating Detect and Heat fabrics show promise for application to other effector types in future.

One very attractive effector fabric would be capable of graphical display. Whether this is based upon electroluminescence, electrophoretic materials, liquid crystals or light emitting diodes as an enabling technology, the pixels will each still need power and control, and thus require a conductive fabric backplane. Another promising fabric effector technology lies in the application of inductor components. Broad, flat fabric components lend themselves well to incorporating antennae and induction coils. Such devices may be concerned with radio signal transmission and reception, or for induced contactless power transmission.

25.3.6 Active non-transducer fabrics

This category of electrical smart fabrics is perhaps the strangest assortment. In the archetypical electronic engineering diagram of a computer or information system, the three building blocks are 'input' (that is, sensors), 'output' (effectors), and between them, the inscrutable 'processing'. Processing here means computation, which equates to logic circuitry and memory, which in turn means transistors and semiconductors. The remaining major class of electrical device which has yet to be represented is prime movers. Prime movers are the source of electrical energy, be they primary or secondary cells (batteries, and rechargeable batteries), photovoltaic solar cells, electromechanical, piezoelectric or thermoelectric generators.

The majority of these prime movers also rely upon semiconductor technology becoming available in some fabric-compatible form. It would seem that semiconductor yarn or fabric is the current frontier in electrical smart fabrics. Their advent is eagerly anticipated, for they promise to bring, amongst many other things, all of the components for a computer that can unfurl like a handkerchief – power source, input devices, memory, processor and display.

25.4 Products and applications

25.4.1 Overview

Textiles can be warm, soft, lightweight, tactile and embracing in contrast to technological devices which by their very nature can be cold, hard, heavy, smooth and certainly unsympathetic to human contact. It is clear why people choose to surround themselves with textile products that are soft to the touch, thermally insulative and breathable. It can also explain why modern technology is often perceived from the outset as being difficult, uncomfortable and alienating?

In ubiquitous computing's seminal 1991 paper, Weiser (1991) states,

> We are trying to conceive a new way of thinking about computers in the world, one that takes into account the natural human environment and allows the computers themselves to vanish into the background.

If computers, and technology in general, are to become as ubiquitous as fabric, it must embed itself successfully into textile products, if only because so much of people's everyday environment is already swathed in fabric. This collision of engineering and textile design disciplines is spawning a new class of soft products that can be startlingly different from their technological predecessors yet as familiar as an old chair or favourite coat.

Having defined and explored the various electrical smart fabric technologies that are of interest at Intelligent Textiles Limited, the following sections examine their applications and products. The discussion is subdivided into the traditional large vertical markets for textile products, namely apparel, furnishings and interior fabrics, healthcare and vehicle interiors.

25.4.2 Apparel applications

Thus far, the majority of take-up on smart fabrics in the apparel sector has been with sports and leisure wear manufacturers. Perhaps this is because they are the branch of apparel that is most comfortable and familiar with technical fabrics, and have a consumer base that demands technical function and advancement. Biometric applications are an obvious starting point, for monitoring both sporting technique and physiological performance. The latter can make use of conductive fabric sensors incorporated unobtrusively into garments, measuring heart rate with integral skin contact electrodes or temperature with passive RTD sensors. Monitoring of sporting technique can be well served by contacting pressure sensors such as Detect fabric. In shoe insoles, pressure mapping fabric can measure plantar pressures, gait or activity levels. Similar technologies can give information about grip technique in bat, club and racquet sports.

Heated garments have an obvious appeal for outdoor activities. The skiing and snowboarding marketplace is clearly very large and affluent, but is still outweighed by the sheer number of smaller niche applications for heated wear, from motorcyclists and scuba divers to pylon riggers and cold-store workers. The limitations of battery technology in these mobile products, as discussed earlier, restrict the scale of electrical heating that can conveniently be applied. At present, we believe that our Heat fabric's ability to concentrate power output and conserve battery life enables genuinely useful products to be manufactured, that can strike a reasonable compromise between cost, bulk, heat output and lifespan. Our glove liner, for example, has a battery lifespan of around four hours when used with a high-capacity lithium polymer rechargeable cell. We also produce a boot liner component, with similar specifications. Heating more of the body than these most vulnerable extremities remains problematic with current battery technology. That said, their pace of development has quickened noticeably, and fuel cell or supercapacitor technology may soon become a realistic alternative.

Incidentally, the technological Philosopher's Stone for this sector of the market is the smart fabric that can cool as well as heat. Phase-change materials are intriguing, but of limited capacity. Far more enticing is the prospect of an actively powered thermoelectric fabric, which can pump heat away from the body as an electric current. The sport and leisure companies are also the most prevalent early adopters of wearable computing concepts. Many such brands currently list high-end garments and accessories that have inbuilt controls for MP3 music players. Accordingly, many smart fabric companies produce components or systems for incorporation into these garments.

As these portable products, such as music players, mobile phones and palmtop computers, become ever smaller, they suffer from the limited space available for their interfaces, as well as being cold, hard, heavy and smooth. For the typical case of a mobile phone, Cochrane *et al.* list the limitations to size as being batteries, keyboard size and display size, in that order (Cochrane *et al.*, 1997). On the second of these limitations, they state: '... multi-function displays and buttons all add to users' operating difficulty. Buttons with four or five functions are not uncommon in the race to reduce size and price.' Reconfiguring these devices to use fabric controls allows their interfaces to be spread over much larger surface areas. The larger controls can be integrated into clothing to eliminate bulk and encumbrance, and even help to make interaction more natural and less intrusive to use, requiring less visual focus. Interactions become gestural, rather than fine manipulation tasks. On the practical side, wearable interfaces cannot be dropped or misplaced, and are always ready for use.

25.4.3 Furnishings and interiors applications

Consider the television remote control. It is a typical small, cold, hard, heavy and smooth technological device, at odds with its soft environment of furnishings, people and pets. Its small size compromises the number, labelling, accessibility and affordance of its control keys. Being cold and hard makes it uncomfortable to sit upon. Being heavy and smooth allows the device to slip efficiently between cushions and become lost. All of these problems can be addressed by a soft device solution using Detect fabric. A remote control built into the upholstery of a chair or a cushion is not small. Its switches can be twentyfold greater in size than a conventional remote control. Nor is the fabric controller heavy, as its size increase has been achieved with little increase in mass or indeed material volume. The keypad has simply been reorganised into a lower profile and lower density package.

The fabric remote control is not hard. It and other soft fabric devices can be at least as robust in general use as the equivalent hard devices. Imagine selecting a material to withstand repeated hammer blows. A typical mass production polymer, such as polystyrene or ABS, will split or shatter. Now imagine trying to destroy a piece of fabric in the same way. This illustrates the distinction between strength (which tends in general to correlate with a material's hardness, stiffness and density) and toughness. Fabric is not strong, or stiff, but can be very tough. Nor is the fabric remote control cold, or smooth. Its fibrous nature imparts it with warmth to the touch and favourable tactile qualities, in addition to arresting its attempts to slip around and disappear.

Whilst this remote control is in itself an interesting and illuminating example of soft product design, it is perhaps more notable for its implications to ubiquitous computing. This type of touch sensor interface can be incorporated into furniture, bedding or carpeting. Detect fabric, as a low-profile, low-complexity, low-cost interface technology can be used to invisibly sensitise all manner of surfaces around us. Expanding upon the example of remote controls incorporated into upholstery and soft furnishings, these can range from simple keypads, to qwerty keyboards, to mouse control tracker pads for the navigation of integrated computerised entertainment systems.

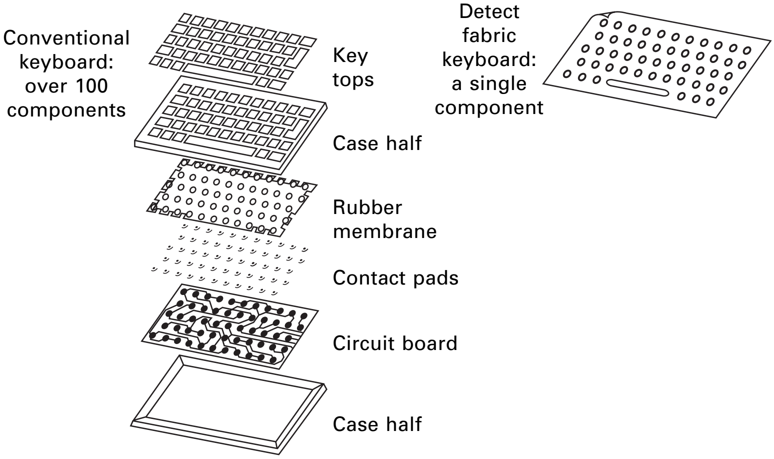
All manner of household textile objects, such as seating, carpets, bedding and towels can be heated, without intrusive heater cables. Heated curtains and carpets might oust ugly radiators and vents, freeing valuable areas of wall in our ever-more compact urban living spaces. Carpets can be sensitised to react to the passage of people. This sensing can be used as a component of intelligent building control, controlling lighting and ventilation according to a room's occupancy. The carpet might monitor the elderly or vulnerable in their homes, discriminating the telltale footprint of a collapsed occupant, lying prone. In public environments, pedestrian traffic could be monitored to aid evacuation, detect intruders or unattended packages, or just glean information for building planning or marketing purposes.

As the technology pundit Bill Buxton has remarked (Harris *et al.*, 1998), 'When people are asked to draw a computer, about 80 percent of the time they draw the I/O devices [interface devices, such as keyboards and monitors].' With these smart fabric transducers now able to replace many of these interface devices, the technology can now begin to disappear, literally, into the very fabric of our surroundings.

25.4.4 Automotive and transport applications

A client from a major European car manufacturer once informed us that their most well-appointed car interior features an extraordinary five hundred individual buttons. In order to service this plethora of switchgear, an additional 14 km of wiring loom is also required. Managing to incorporate this many controls, without resorting to a 'flight deck' aesthetic, has become a grave design issue. Electrical smart fabrics like Detect can serve to rationalise many of these controls and their wiring into the existing textile upholstery components, door panels and headlining, thus greatly reducing the component count.

By way of example, Fig. 25.2 illustrates a conventional qwerty computer keyboard, exploded into its hundred or so constituent components. The corresponding Detect fabric keyboard, with a similar number of discrete pushbuttons, streamlines this into a single component. As well as reducing cost, complexity and component count, upholstered controls can also reduce weight. This is particularly relevant in the aerospace industry, where another client claimed that every extra kilogram carried by a commercial airliner costs over $100,000 per annum in additional fuel.



25.2 A conventional qwerty computer keyboard, exploded into its hundred or so constituent components.

Within the seats themselves, the most obvious candidate technology is Heat fabric. Within the same fabric panels, or as an underlay to leather upholstery, Detect switches can discriminate between adult and child occupants, and thus inform intelligent safety systems whether to deploy airbags and seatbelt tensioners in an accident, and with what force. Eventually, one might envisage a wholly textile car interior, where the fabric components form a continuous backplane and medium for the majority of the switchgear, interior illumination and even displays for instruments and entertainment devices.

25.4.5 Healthcare applications

As in sporting apparel applications, a major healthcare application for electrical smart fabrics is biomonitoring. The sensing of a patient's physiological variables might take place through their bedding, seating or clothing, but in any event could include electrodes for electrocardiography, RTDs for skin temperature, some configuration of strain or pressure sensors for respiration, and even give warning that moisture has been detected.

In bedding, pressure mapping fabrics might also monitor for the areas of increased load and prolonged inactivity that result in the formation of pressure ulcers. Pressure ulceration poses serious problems for bedridden or paralysed patients, and exacts a devastating cost, both financial and in quality of life. All of these techniques are easily transferable from ward beds to operating tables, to wheelchairs and neonatal cots. In cots, particularly, much of this may also find consumer product applications. The same pressure sensitivity in seats or mats can help monitor posture or technique during rehabilitation and occupational therapy.

Turning to medical dressings, sensors intrinsic to the fabric of surgical gauze, bandages or splinting materials may allow the examination of wounds without their continued re-exposure and re-dressing. Resistive moisture sensors may detect bleeding, or give a measure of alkalinity, indicative of infection. Stabilised electrical heating may be applied to relieve pain or accelerate the healing of wounds. Conversely, phlebology dressings that are designed to slow healing, and thus reduce scarring, by constricting a wound might be monitored to ensure they apply the correct pressure. Healthcare is a market sector where technology is in particularly intimate contact with our skins, or even underneath it. The imperative to make technology soft and sympathetic is at its strongest here.

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