15
Medical applications of smart textiles

S. COYLE and D. DIAMOND, Dublin City University, Ireland

DOI: 10.1533/9780857093530.3.420

Abstract: Smart fabrics and interactive textiles are a relatively new area of research, with many potential applications in the field of biomedical engineering. Sensors integrated into textiles in contact with the body have the ability to capture many useful physiological signals. This chapter discusses some of the signals that can be measured using smart textiles and examples of the application of this technology. Future trends in this area of research are presented and issues regarding technology development and its uptake are highlighted.

Key words: smart textiles, wearable sensors, biomedical engineering, physiological measurement, wearable chemosensors, textile sensors, functional fabrics, connected health.

15.1 Introduction

Medical engineering aspires to improve human well-being and promote health through the creation of devices for diagnosis, treatment and cure of medical conditions. Some devices are designed to analyse the physiology of the human body, such as ultrasound imaging or the familiar stethoscope. Other devices function as assistive tools, where the body's system has weakened, such as hip replacements or orthotic limbs. The development of new materials and the miniaturisation of electronic devices have resulted in great advances in this largely multidisciplinary field. Medical engineering combines the skills from engineering, scientific and medical communities. A surge in multidisciplinary research in the 1960s and 1970s led to many advances in modern healthcare, based on breakthrough discoveries in biomedical engineering (Fagette, 1997; Bronzino, 2000). Developments in microelectronics and material science have helped to miniaturise many of these technologies. The first electrocardiograph, to monitoring heart function, developed by Einthoven at the beginning of this century, weighed about 600 pounds and required 5 people to operate it (Street, 2008). In the 1960s, portable Holter monitors were being used in clinical settings to allow 24 h monitoring of patients. Today, with the advances in smart textiles, it is possible to measure heart rate through the clothes we wear and link up this information to wristwatches or mobile phones.

Smart fabrics and interactive textiles are a relatively new area of research, with many potential applications in the field of biomedical engineering. The ability of smart textiles to interact with the body provides a novel means to sense the wearer's physiology and respond to the needs of the wearer. Wearable sensors and smart fabrics in principle have the ability to sustain the health and wellness of the wearer. Clothing that we don for hours each day has the capacity to continuously monitor the physiology of the wearer. Physiological signals, such as heart rate, breathing rates and activity levels, are useful indictors of health status. These signals can be measured by means of textile-based sensors integrated into smart clothing. Smart garments have the potential to offer a personalised healthcare solution, by making the wearer more aware of their health status. This would thereby encourage individuals to take a more active role in their own healthcare.

The advantage to medical practitioners is a more thorough insight into their patients' well-being in the home setting. This provides a full picture rather than snapshot clinical visits, which may miss important events. Wearable sensing devices can give doctors quantitative measures of how their patients are progressing at home. Doctors rely on patients' accounts of how they feel. Patients often tend to misreport the severity of their condition. Smart clothing has the ability to keep a digital record of the patient's physiological response since their last clinical visit, allowing doctors to make a more accurate diagnosis. Similarly, in rehabilitation, it is difficult for therapists to ensure that patients are complying with prescribed exercises. Smart garments sensing body movements have the potential to guide wearers through their exercises, while also recording their individual movements and adherence to their prescribed programme. This detailed information gives a quantitative measure of improvement since the last clinical visit. Through long-term monitoring, medical staff have a broader window into the person's condition and can provide more personalised care. This extends from lifestyle and health status management to individualised medicines and treatment.

15.2 Monitoring of body parameters

Most of the existing wearable technologies are based on physical sensors, such as electrodes, thermistors and accelerometers. These sensors respond to physical changes in their environment, for example electric fields, heat and movement. Textile electrodes can be used to detect electric signals from the body, such as electrocardiography (ECG) from the heart and electromyography (EMG) from skeletal muscles. Textile strain gauges and pressure sensors can detect body movements, such as breathing movements and foot pressure. Accelerometers pick up speed of movement and depending on placement, can focus on a specific limb or determine the body's general activity level. An emerging field in the area of wearable sensors is in wearable chemo-sensors. These devices have the potential to measure many more variables relating to the person's well-being and safety. Chemical sensors have an active surface, which reacts or interacts with a sample at the molecular level, for example through the use of immobilised receptors that selectively bind a particular target species, and in so doing generate an observable signal (Janata, 2009). Wearable chemo-sensors can monitor the composition of

Table 15.1 Physiological signals that may be measured using textile based sensors

Physiological measurement	Textile-integrated sensors	Signal source	Typical sensor placement
Breathing patterns	Piezo-resistive stretch sensors, inductive plethysmography, impedance plethysmography, optical fibres	Expansion and contraction of ribcage during breathing	Thoracic-abdominal region
Heart activity	Woven/knitted electrodes	Electrical activity of heart	Thoracic region
Muscle activity	Woven/knitted electrodes	Electrical activity of muscles	Skin surface overlying relevant muscles
Blood oxygen saturation	Optical sensing components, plastic optical fibres	Light absorption of haemoglobin in blood	Regions with good blood perfusion, e.g. finger tip, earlobe
Blood pressure	Features of the photoplethysmography (PPG) signal	Arterial pressure pulsations	Finger, wrist and earlobe
Body movement, posture	Piezo-resistive strain/ pressure sensors, accelerometers, gyroscopes, optical fibre sensors	Body kinematics	Dependent on motion to be analysed
Electrodermal activity	Woven electrodes	Skin electrical conductivity	Fingertips
Composition of body fluids	Electrochemical sensors, colorimetric pH fabric	Composition of sweat, saliva, urine	Fluidic sampling system necessary

body fluids, such as sweat, saliva, tears and urine. There are also potential biomarkers from gaseous samples in breath and perspiration. Table 15.1 lists some physiological parameters that have been widely studied using textile-based sensors.

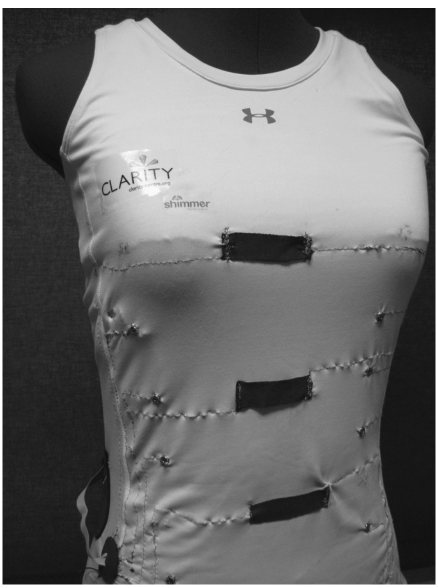
15.2.1 Breathing

Breathing is closely related to our physiological and psychological state. Breathing patterns can be monitored by measuring changes in thoracic volume as the ribcage expands and contracts with each breath. This movement can be detected using wearable strain gauge sensors or using textile electrodes for electrical impedance or inductance plethysmography.

Textile-based strain sensors have been demonstrated using stretch fabrics modified with inherently conductive polymers (Rovira Carlos, 2011) or carbon loaded rubbers (Tognetti *et al.*, 2005). Knitting with conductive yarns is another approach to creating textile piezo-resistive sensors (Loriga *et al.*, 2007). Stretch of the textile sensors leads to a change in conductivity of the material. The use of multiple sensors allows not only the breathing rate to be measured, but also gives an indication of the amplitude of breathing, for example deep breathing manifests as a large change in signal amplitude. A respiratory monitoring vest, developed by the Adaptive Sensors Group in Dublin City University in collaboration with Shimmer Research (www.shimmer-research.com), is shown in Fig. 15.1.

Electrical inductance plethysmography integrates two conductive wires into a garment, one around the ribcage and the other around the abdomen. Motions of the chest wall cause changes of the self-inductance of the two loops. Impedance pneumography uses two or four textile electrodes placed at the thorax. It involves injecting a high-frequency and low-amplitude current through the electrodes and measuring the trans-thoracic electrical impedance changes. This technique has been used in projects such as myHeart and WEALTHY (Paradiso *et al.*, 2005(b); Paradiso and DeRossi, 2006).

An alternative approach to monitoring breathing is using textile-integrated optical fibres. The OFSETH (http://www.ofseth.org/) project aims to develop new



15.1 Respiratory monitoring shirt with integrated piezo-resistive sensors. Data is acquired and wirelessly transmitted using a Shimmer™ device.

monitoring devices for various vital parameters by embedding optical sensors into textiles using textile processes optical fibres. To monitor breathing, fibres were stitched onto textile in a sinusoidal shape. The fibres were illuminated with a laser and light detected with photodiodes. The curvature of the bends affected the light attenuation through the fibre. Analysis of the bending of these fibres was used to recognise the breathing movements of the wearer's upper body. This technology has the advantage of being compatible with MRI scanning (D'Angelo *et al.*, 2008).

15.2.2 Heart activity

ECG records the electrical activity of the heart from the skin surface. With each heartbeat, an electrical signal spreads from the top to the bottom of the heart. As it travels, the signal causes the heart to contract and pump blood. Analysis of the timing and morphology of the electrical signal can help to diagnose heart problems. ECG is typically measured using silver chloride electrodes coupled to the skin with gel. In clinical settings, 12 electrodes are used, which allows the heart's activity to be viewed from 12 different angles; 3 and 5 lead portable systems, such as a Holter monitor, are used when continuous monitoring is needed, but these require wires and adhesive electrodes to be placed on the body.

Flexible conductive yarns, fully metal yarns, or natural/synthetics blended with conductive fibres have been knitted into garments to develop textile electrodes (Catrysse *et al.*, 2003). A study by Paradiso *et al.* (2005(a)) shows good correlation between fabric electrodes and traditional silver/silver chloride electrodes. A major issue with bio-potential electrodes is the need to use a gel to provide a good contact between the sensor and the skin. This restricts the ease of use and can cause skin irritation. In recent years, much effort has been focused on the development of 'dry' electrodes. Dry electrodes are well suited for long-term monitoring, although they are subject to more noise interference, particularly from motion artefacts and power line interference (Xu *et al.*, 2008; Merritt *et al.*, 2009).

15.2.3 Muscle activity

EMG is a method of measuring electrical activity from muscle. Surface EMG (sEMG) technology allows information regarding the overall muscle function and condition to be collected from the surface of the skin in a non-invasive manner. Intramuscular EMG involves the use of a needle electrode to penetrate directly into the muscle, giving a more localised measurement about muscle fibre activity. This method is primarily used as a diagnostic tool to detect very subtle changes of electrical muscle activities to determine underlying disease processes. For wearable applications, surface EMG is more useful and feasible and has applications in biofeedback relaxation and in rehabilitation. Traditionally, disposable metallic (Ag/AgCl) EMG electrodes with conductive paste are glued to the skin upon the muscles of the person under the test. An EMG device can give a patient feedback on how hard he or she is exercising an injured muscle and provide an evaluation of muscle function to monitor improvement with therapy. A study by Finni *et al.* (2007) showed that the signals from textile electrodes are in good agreement with traditionally measured surface EMG signals. In the textile electrodes, the shape and size of the conductive area and the inter-electrode distance are different and much larger than in the traditional Ag/AgCl electrodes. The larger conductive area is not so sensitive to slight differences in electrode positioning in longitudinal studies as compared to the traditional electrodes. However, the larger area is not muscle-specific but collects data from entire muscle groups, which can be an advantage in conditions where information on precise motor control is not required.

Another application of EMG is in the control of prosthetic devices. Textile electrodes embedded into a garment are a straightforward means of electrode placement. A recent study demonstrated that e-textiles can be used as recording systems for highly accurate EMG control of hand and wrist functions for active prostheses. A sleeve with high-density electrode grids covering the upper and lower arm was used to record EMG signals (Farina *et al.*, 2010).

The ConText project, funded under EU FP6, involved the development of a vest that measured a sEMG signal with textile integrated sensors, without direct electrical skin contact. Textile electrodes were embroidered into a garment and functioned as capacitive transducers measuring through a textile layer (Linz *et al.*, 2007). The possibility of avoiding direct skin contact reduces skin irritation problems. When using traditional electrodes, the skin is usually prepared by shaving, abrading and cleansing, which can cause irritation.

15.2.4 Blood pressure

Blood pressure is an indication of the amount of work that the heart has to do to pump blood around the body. A traditional blood pressure meter, known as a sphygmomanometer, comprises an inflatable cuff to restrict blood flow and a mercury or mechanical manometer to measure the pressure. A stethoscope is used to listen to the pulse to take a pressure reading when the heart muscles contract (systolic pressure) and when the heart muscles relax (diastolic pressure). Automated electronic devices are beginning to replace the traditional manual sphygmomanometers and this technology has led to portable ambulatory monitoring devices (Pickering *et al.*, 2005). A wrist-worn device available for home use is available from Omron Healthcare (http://www.omronhealthcare.com). The Omron Wrist Blood Pressure Monitor takes periodic blood pressure readings and stores the readings to memory with a time stamp. Blood pressure varies at different times during the day, and night-time levels are important for diagnosis.

Blood pressure can also become elevated due to anxiety. This can lead to 'white coat hypertension,' where anxiety in the doctor's surgery causes a reading that is higher than normal. Therefore, to get a true picture of the patient's blood pressure, ambulatory monitoring is necessary. Ideally, this should be carried out in a discrete manner. Earlier systems made a loud sound when the cuff was being inflated or deflated. Harry Asada's group, at the Massachusetts Institute of Technology, have been developing wearable blood pressure monitors based on features of the pulse signal (Asada *et al.*, 2010). Photoplethysmography (PPG) is an optic signal related to the volumetric pulsations of blood in tissue, which in turn is related to arterial pressure pulsations (Reisner *et al.*, 2008). Rather than using the traditional occlusion cuff, Asada *et al.* (2010) created a device that uses two in-line PPG sensors. One sensor was placed against the ulnar artery at the wrist and one was placed against the digital artery of the little finger. This measured the peripheral pulse transit, which can be correlated with important arterial blood pressure. The device is being commercialised by CardioSign, a company launched by a former group member, Philip Shaltis (Trafton, 2009). Another device has been developed by Tatara *et al.* (2007), to monitor blood pressure. The device is small, lightweight and designed to be worn on the ear. It has the advantage of being unaffected by arm movement. Although these devices are wearable, they are not textile-based. However, the ability of optical fabrics to detect PPG signals (Selm *et al.*, 2010) imply the potential for smart-textile blood pressure monitors.

15.2.5 Blood oxygen saturation

Blood oxygen saturation is a measurement of the amount of oxygen attached to the haemoglobin (Hb) cells in blood. Pulse oximetry is a simple non-invasive method of monitoring the percentage of Hb in blood, which is saturated with oxygen. In a fit, healthy individual, this is usually above 95%, although it varies with degree of fitness and current altitude. A pulse oximeter works by measuring the absorption of light through body tissue with a high perfusion rate of blood, usually at the finger or earlobe. Hb has a different absorption spectrum, depending on whether it is oxygenated (oxy-haemoglobin) or deoxygenated (deoxy-haemoglobin). Oxygen saturation (SpO_2) is estimated by measuring the absorption of two different wavelengths of light through the tissue. LEDs are typically used as light source and photodiodes as light detectors. These optical components may be placed in a transmission mode configuration, on either side of the tissue, or else in reflectance mode on the same side of the tissue. Photonic textiles using OLEDs or woven polymer optical fibres (POFs) offer an alternative to conventional LEDs, to create a textile-based pulse oximetry system. Rothmaier *et al.* (2008) have demonstrated such as system, using a cotton glove with woven POFs positioned at a fingertip of the glove.

The disadvantage of using fingertip or earlobe probes is that they may interfere with the user's daily activities. A pulse oximetry sensor using optical fibres integrated into fabric has been demonstrated to measure blood oxygen saturation at the sternum (Solà *et al.*, 2007).

15.2.6 Body movement

There are many variations of textile-based and wearable sensors to monitor movement of the body. The configuration depends on the motion under analysis and the application. Monitoring body movement can give an indication of general activity, which may be useful in monitoring the well-being of isolated individuals or motivating patients to maintain a daily activity level in the case of obesity or cardiovascular disease. Measuring specific motions has applications in rehabilitation therapy. Monitoring characteristics of the body's movement is also useful in assessing conditions affecting motor skills, such as Parkinson's disease.

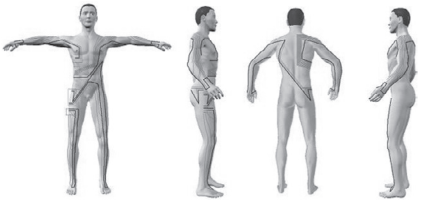
There are two main approaches in smart garments for monitoring biomechanics. One area is in the use of inertial sensors together with advanced algorithms, the other area is the development of textile-based sensors (De Rossi and Veltink, 2010).

Fabric-based sensors, which respond to stretch or pressure, can be used to capture kinematic movements of the body. Fabric stretch sensors can detect movement of the limbs by placing sensors across joints, such as the knee or elbow. The sensors may also be placed on the back, to examine posture of the spine and upper body position and gestures. Danilo De Rossi's group, at the Interdepartmental Research Centre 'E. Piaggio,' University of Pisa, in collaboration with Smartex Srl (www.smartex.it), have developed various garments to measure biomechanics. Conductive loaded rubbers have been integrated with textiles as sensing elements and as conductive tracks to data acquisition units (Carpi and De Rossi, 2005). An upper limb kinesthetic garment, which detects the posture of wrist, elbow and shoulder, has been developed for post-stroke patient rehabilitation. A photo of this garment and a conceptual diagram of such kinematic garments are shown in Fig. 15.2. This garment can be integrated into a healthcare service, which allows patients to continue the rehabilitation training at home without the help of physicians, after the intensive rehabilitation period (Tognetti *et al.*, 2005).

Gerhard Tröster's group, in ETH, Zurich, have also developed a prototype garment that can recognise upper body postures using textile strain sensors. A strain sensitive fibre was made using a mixture of a thermoplastic elastomer and carbon black particles. The fibre was extruded using a capillary rheometer. It was integrated into the back region of a tight fitting garment, using conductive thread and conductive epoxy (Mattmann *et al.*, 2008). A further study with this smart garment involved the identification of exercise execution on a gym machine to measure the intensity of training and dynamics of movement (Mattmann *et al.*, 2007).

These sensor garments offer potential aids to physiotherapists and their patients. At present, therapists monitor and regulate exercises performed by patients during therapy sessions and encourage patients to continue self-exercise programmes.

(a)



(b)

15.2 (a) Post-stroke rehab garment. (b) Conceptual diagram for the design of kinematic sensing garments developed by Interdepartmental Research Centre 'E. Piaggio', University of Pisa and SMARTEX Srl. (Photo courtesy of Professor Danilo De Rossi.)

Patients need to be kept motivated between therapy sessions, to carry out their prescribed exercises. Lack of adherence to prescribed exercise is a common problem and delays recovery. It is very easy for subjects to become distracted and unmotivated in performing the exercises at home. In some cases, debilitating conditions may lead to depression and lack of self-motivation, leading into a cycle that stalls progress. Smart garments have the potential to inform therapists about what exercises have been carried out and whether they have been performed correctly. At the same time, they can be connected to a user interface providing guidance and feedback to patients.

Another important clinical application of biomechanical sensors is in monitoring and aiding management of conditions, such as Parkinson's disease. Currently, clinical visits are inadequate to sample the severity of Parkinsonian symptoms, because symptoms vary in response to medication dosage and can affect a patient's perception of their own motor status. Therefore, there is a need to gather objective measures of the severity of symptoms over time, to reliably assess the effectiveness of medication adjustments (Bonato, 2010).

Fall detection is another key application of wearable kinematic sensors. Approximately 28 to 35% of people aged 65 and over fall each year, increasing to 32 to 42% for those over 70 years of age (World Health Organisation, 2007). The frequency of falls increases with age and frailty level. Approximately one-quarter of falls result in physical injury and incur high costs in terms of quality of life and to health and social services. Falls may also result in a post-fall syndrome, which includes dependence, loss of autonomy, confusion, immobilisation and depression, which will lead to a further restriction in daily activities. Typically accelerometer-based devices are used to detect falls, the principle being that the fall has a different pattern of motion compared to other activities. While accelerometers are low-cost and relatively easy to position on the body or in a walking stick, the classification of falls is a complex task, which can often lead to many false alarms. Yu (2008) gives a survey of fall detection for elderly patients, focusing on identifying approaches and principles of the existing fall detection methods. Perry *et al.* (2009) have also published a survey of fall detection methods, with evaluations based on their own results. Their study found acceleration to be a critical role in elderly mobility monitoring, and should be used in fall detection. Compared to visual and acoustic sensors, accelerometers consume less energy and are much easier to integrate into wearable mobility monitoring devices. The Technology Research for Independent Living (TRIL) Centre has a central research focus on fall detection and prevention. The centre aims to elucidate the factors contributing to falls and to use this information to develop assessment tools to identify those at risk of falls (http://www.trilcentre.org/falls-prevention-research).

15.2.7 Electrodermal activity (EDA)

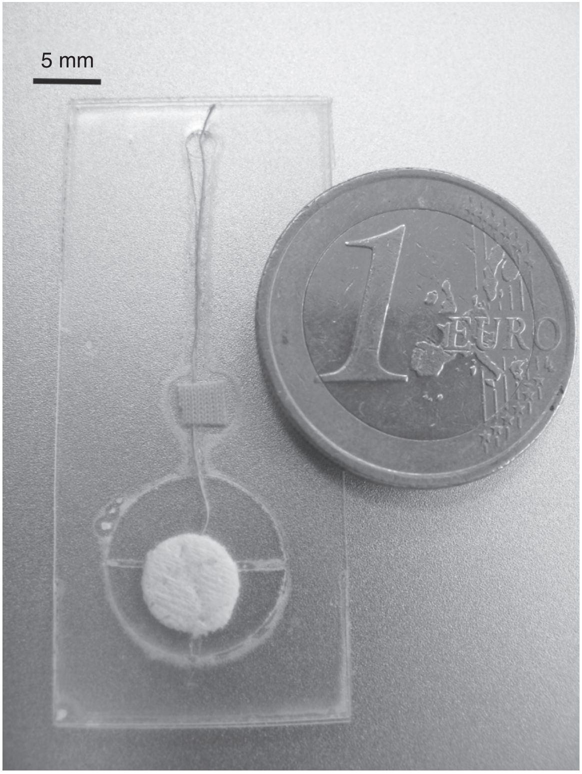
Emotional reactions often cause increased sweat gland activity on the palms of the hands and the soles of the feet. The baseline level of skin conductance varies from person to person and depends on both patient physiological state and autonomic regulation. This baseline varies slowly over time, indicating the general activity of the perspiratory glands that may be affected by factors such as temperature. A faster phasic change or 'peak' in skin conductance can occur as a result of a specific stimulus or event. This response appears between 1.5 and 6.5 seconds after the stimulus. Electrodermal activity (EDA) is generally measured by placing silver-silver chloride electrodes on the first and second fingers of either one or both hands. One electrode emits an electrical signal, whilst the other primarily acts as a receiver, thus a circuit is established that passes across the skin. Prototype gloves and socks have been developed to measure the EDA response in a wearable manner. The MARSIAN smart glove (Axisa *et al.*, 2004) was developed to measure the activity of the autonomic nervous system by measuring physiological parameters of the skin. Two prototypes were developed, the first based on Kapton/copper foil and the second was a hairnet structure with standard silver/silver chloride electrodes embroidered into it. The European Union PSYCHE and MONARCA projects have also developed garments measuring EDA, as part of a system to support the diagnosis and treatment of bipolar disorder patients (Gaetano Valenza, 2010; Kappeler-Setz *et al.*, 2010). The MONARCA project has shown the integration of the sensor system in the shoe or sock as a promising approach. EDA peaks at the foot occurred around 0.5 seconds later than the EDA peaks at the hand. The context of the user, such as the outside temperature and clothing, needs to be taken into account when measuring and analysing EDA traces, as this affects the evaporation of sweat from the skin. In the PSYCHE project, the hands and feet have been used for measuring EDA. Another study by Poh *et al.* (2010) has demonstrated a wrist-worn sensor that measures EDA from the forearm.

15.2.8 Composition of body fluids, sweat analysis

Wearable chemo-sensors can be integrated within a garment to access body fluids (Coyle *et al.*, 2010a). Blood is the most reliable diagnostic medium; however, as it requires invasive techniques for sampling, it is typically sampled at specified time intervals. Therefore other body fluids, which can be accessed more easily through non- or minimally-invasive means, must be considered for continuous analysis. Possible samples include urine, saliva, sweat, interstitial fluid and wound exudate. Of all these body fluids, sweat is the most accessible within a garment structure. Sweat is a filtrate of blood plasma and contains many substances of interest, such as sodium, chloride, potassium, bicarbonate and calcium (Shirreffs and Maughan, 1997) (Fig. 15.3). Sweat analysis offers valuable physiological information. The sweat test, measuring sodium and chloride concentration levels, is the gold standard technique for the diagnosis of cystic fibrosis (CF). Sweat composition is highly variable among individuals and is also affected by environmental conditions and activity levels.

Analysis of sweat loss and sweat composition can offer valuable information regarding hydration status and electrolyte balance, which is vital for our well-being. Analysis of sweating patterns during the day and night-time may be useful for monitoring patients with conditions such as diabetes and hyperhydrosis (Haider and Solish, 2005; Asahina *et al.*, 2008).

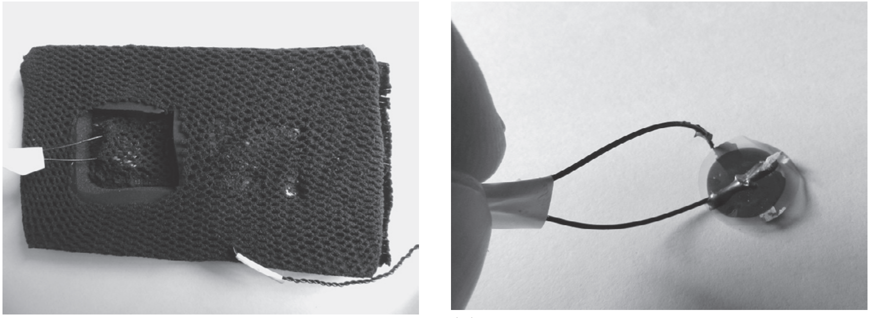
The most widely-used methods of sweat analysis to date involve the collection of sweat by using patches or pouches and then analysis afterwards using a standard measurement technique (Brisson *et al.*, 1991). The BIOTEX project developed a textile-based system to collect and analyse sweat, by using a textile-based sensor



15.3 Microfluidic chip for analysis of sweat pH. (Photo courtesy of CLARITY, Dublin City University.)

capable of performing chemical measurements. This work demonstrated the use of a fabric-based patch to measure sweat pH, sodium and temperature and a textile-based sweat rate sensor utilising humidity sensors (Coyle *et al.*, 2010a, Salvo *et al.*, 2010). The sweat rate sensor (Fig. 15.4), integrated two humidity sensors in a textile structure at two distances (0.5 and 1.5 cm) from the skin. Sweat rates were estimated from the gradient of humidity measured by these devices. Recent work by Benito-Lopez *et al.* (2010) has involved a miniaturised microfluidic sensing platform for real-time sweat analysis. Figure 15.3 shows a microfluidic chip used to collect sweat samples for real-time analysis of sweat pH. The fluidic channel contains a pH sensitive material, which changes colour, depending on sweat pH.

Yang *et al.* (2010), at the University of California, San Diego, have demonstrated printed biosensors in clothing. Electrochemical sensors were printed directly onto the elastic waist of underwear that offers tight direct contact with the skin. The group plans to incorporate chemically-selective layers, which can detect substances, such as ethanol or lactate.



(a) (b)

15.4 (a) Sweat rate sensor developed at University of Pisa during the BIOTEX project. (b) Humidity sensor integrated into textile pockets of the sensing device at different distances from the skin. (Photo courtesy of Dr Fabio Di Francesco.)

Another approach to sweat detection has been demonstrated by Vaughan and Scully (2008). Polymer optical coatings to detect moisture were developed to clad POFs. A POF sensor has been integrated into a garment that can be worn during daily activity and is unobtrusive. The plastic optical fibre sensors were designed to continuously monitor human perspiration in response to changes in environmental conditions, physical and mental activity, medical condition or psychological stress.

15.3 Challenges in medical smart textiles

There is no doubt that wearable technologies have much to offer to the medical sector, such as continuity of care from early detection through to home therapeutic and rehabilitation aids. They have the potential to introduce more personalised care and to encourage people to take a more active role in their health and well-being. This will hopefully help to reduce the demand on future healthcare systems and result in more efficient care. In order for this technology to become widely accepted, there are a number of challenges that must be overcome.

15.3.1 Wearability

Wearable technologies should be soft, flexible and washable, to meet the expectations of normal clothing. Washing is an important factor in terms of product lifecycle. The first wearable computers were bulky and rigid and were really more 'portable' rather than 'wearable' systems. With increased miniaturisation of electronic devices and the advances in functional materials, wearable technologies are becoming more integrated into the textile structure. By adding function to the fabric and creating a fabric sensor, the smart garment can retain its normal tactile properties. The design of smart garments and sensor integration depends on the application, the users' needs and what measurements are most useful (McCann *et al.*, 2005). A smart garment must be suited to the user, for example a smart jacket for a neonate must be designed for minimum stress when dressing (Chen *et al.*, 2010).

Ideally, all the components that constitute a smart garment, including power, sensors and electronics, would be textile-based and washable. In reality, there are limitations with these components. Advances in flexible batteries (Liu *et al.*, 2012) and textile transistors (Barbaro *et al.*, 2010) show promise for the future; however, until such a time, electronic modules need to be sealed or removable. They should also be packaged without sharp edges, which could be hazardous, and should be positioned in an ergonomic manner. Sensors have the issue of calibration. In particular, chemical on-body sensors require an active surface to react. One solution to avoiding calibration is to use low-cost sensing elements, which can be replaced. An example of this is a sweat sensing device, where the microfluidic chip can be easily replaced, while the optical and electronic components are re-useable (Curto *et al.*, 2012).

Fabric sensors can be easily integrated into garments and connected by using embroidery or weaving techniques using conductive threads. While there have been developments in flexible antennae, the wireless electronic components are generally conventional electronic devices. These must be packaged carefully to ensure user safety and comfort. Methods of interconnection between flexible textile conductive traces and conventional electronics include crimping, soldering and embroidery. There is a pressing need for a common set of standards defining methodologies, specifications and best practices for the various smart-textile applications and products. Due to the young nature of smart textiles, standards to evaluate the performance and compatibility in healthcare are missing and it remains to be seen if available medical or electronics standards can be applied (Schwarz *et al.*, 2010). A European task group (CEN/TC 248), led by Belgian CentexBel, was established in 2006 to develop guidelines for the development of standards for smart textiles. There is a need for international standards and regulations, a need for common certification of smart textiles and garments, and a common certified validation protocol and quality control during production (Lymberis and Paradiso, 2008).

15.3.2 Ease of use

Portable monitoring devices often involve wires and may require electrodes to be positioned and adhered. What could be simpler than putting on a 'smart' shirt, which has inbuilt sensors in the right places to monitor vital signs? The goal of smart garments is to enhance everyday clothing and to increase its functionality for the benefit of the wearer. The garment needs to be straightforward to use and a suitable user interface is needed. Data must be presented to the user in a useful manner, without overloading the user with too much data. Much of the research in wearable technologies and personal health systems has focused on monitoring patients; however, one of the largest challenges still remains and that is in the design of methods of user feedback. This needs to be designed to suit its purpose, for example, for a respiratory feedback system for children with respiratory illness, an avatar game has been developed to provide assistance and motivation (Mitchell *et al.*, 2010). The system was designed to be accessible, requiring a web-browser to run a Flash application. Another project carried out by CLARITY, DCU and NUIM, was a stroke rehabilitation glove, which was designed to provide physiotherapists and patients with animations of hand movements. An oedema glove was used to integrate the sensors; such a glove would be familiar, as it is typically used to reduce swelling of the hand in stroke patients (Coyle *et al.*, 2010b).

There are many signals that can be measured from the body; however, the big question is how to use this information in a way to benefit the user? In order to do this, multiple data sources need to be carefully processed into a useful index to give an overall picture or to highlight changes and unusual physiological events. New algorithms are needed to do this, taking into account the user context. Data should be transmitted and stored automatically with minimum effort from the wearer. In two separate blood pressure studies, it was found patients fabricated readings when asked to record their blood pressure measurements. The patients were not aware that the readings were stored to memory cards during the studies (Pickering *et al.*, 2005).

15.3.3 Acceptance by medical profession

Sensor systems become redundant if patients or clinicians do not want to work with them. A review of patients' and clinicians' preferences for non-invasive body-worn sensor systems was carried out by Bergmann and McGregor (2011). The key user preferences were that a body-worn sensor system should be compact, embedded and simple to operate and maintain. It also should not affect daily behaviour nor seek to directly replace a healthcare professional.

The integration of personal health monitoring systems in healthcare implies their interconnection with existing health information systems and electronic health records. Therefore it is essential to ensure interoperability with current- and future-generation communication infrastructure – broadband, fixed and wireless (Gatzoulis and Iakovidis, 2007). Studies need to be carried out to help convince the medical community of the benefits of this technology. These studies need to investigate the impact on quality of life and it must be demonstrated that this technology can help to reduce hospitalization rates and quality of care.

15.3.4 Ethics

Physiological data of users are a highly personalised and private source of information. Important medical and lifestyle trends can be gleaned by analysing the physiological data from large populations. Concerns about patient privacy, trust, product liability and negligence in handling medical data are affecting the adoption rate and usage of current electronic health systems (Sarabdeen, 2012). There is currently an inadequate level of legal protection or unawareness of availability of laws and regulation that addresses the electronic healthcare system privacy. With the increased use of information systems in society, user privacy is becoming an issue of major social concern. Data containing personal information requires security in storage, transmission and third-party use. It is vital to ensure that encryption and security methods are in place. Computer misuse, common to the internet, is a potential risk.

The sharing of patient data between different healthcare professionals, departments and other information systems could affect the confidentiality of a patient's data or it could compromise the integrity and timeliness of the treatment of the data (Whitehouse and Duquenoy, 2011). These threats are extremely difficult to address technologically and enforce internationally (Duquenoy and Whitehouse, 2010). Patient confidentiality must be preserved and the users' informed consent must be given to use this data. Given that a user may have little knowledge and lack of control of the information system handling the data, we need to ask to what extent and in what way, the particular user is 'informed' of the system (Duquenoy and Whitehouse, 2010). Another potential ethical impact on users is compatibility – if the user is tied in to one particular system platform and its applications, this raises issues of affordability and opportunity for equal access. Reliability is another concern, particularly where systems are life-critical. Users need to be made aware of how reliable the systems are.

15.4 Trends and applications of medical smart textiles

Given the range of physiological signals that smart textiles can sense, there are many scenarios where they can be applied. Cardiovascular diseases represent the leading cause of deaths worldwide and much of the research in wearable and portable eHealth systems has focused on these diseases. The non-invasive monitoring capability of these systems concerns not only the prevention of cardiovascular diseases (e.g. myocardial infarction and stroke) but also their management, as in the case of chronically-ill patients (Gatzoulis and Iakovidis, 2007). Since the mid-1990s, the European Commission (EC) has developed innovative systems and services for personal health monitoring. A number of collaborative research projects (AMON, MOBIHEALTH, WEALTHY and MYHEART, to name a few) have been funded by the Fifth and Sixth Research Framework Programme of the EC (FP5, FP6). Recent projects, part of the Seventh Research Framework Programme (FP7), have brought a focus onto mental health, including projects such as PSYCHE.

One of the first commercial smart garments that became available was the Lifeshirt® developed by Vivometrics (Heilman and Porges, 2007). The shirt contained respiratory function sensors woven into the shirt around the patient's chest and abdomen, a three-lead, single channel ECG and a three-axis accelerometer to record subject posture and activity level. The Smart Shirt by Sensatex was developed around the same time, based on technology from Georgia Tech (http://www.gtwm.gatech.edu/), funded by the US navy. The shirt contained optical and conductive fibres integrated into the garment to monitor vital signs. The optical fibres allowed the detection of a bullet penetration and its location for law enforcement and military applications. The shirt was designed to be used for physiological monitoring in various scenarios, including chronically-ill patients, elderly persons living alone, athletes and infants.

Exmovere Holdings have now developed a garment based on patents licensed from Sensatex and Georgia Tech. The Exmobaby garment is a baby sleep garment to measure vital signs. Thanks to embedded electrocardiogram, skin temperature, moisture and movement sensors, the Exmobaby system wirelessly transmits a baby's vital sign data to a PC located within 100 feet. Smartlife Technologies (http://www.smartlifetech.com), based in Manchester, also offer a monitoring shirt called the SmartLife HealthVest®. The garment is created with integrally knitted ECG electrodes, respiratory sensors and conductive pathways. Doubled covered elastomeric yarn is used for the base structure and silver coated yarn for the sensors and conductive pathways. A three-dimensional (3-D) image of the knitted garment is shown in Fig 15.5. Zephyr Technologies (http://www.zephyr-technology.com/) have developed a BioHarness™ to measure critical vital signs (ECG, heart rate, breathing rate, skin temperature) and contextualise the information with the individual's physical activity using an accelerometer (activity and posture). The device is available in strap or clothing form and can link to a smart phone, PC or web portal. The device is designed for use by first responders, military, personal trainers and professional sports teams. The device was used to monitor the 33 Chilean miners that were trapped in the San Jose mine in 2010.

Underarmour have teamed up with Zephyr to develop the E39 compression shirt, which measures heart rate, breathing rate and G Force information. It combines with the Omnisense software to develop automatic tests for fitness and vertical and broad jumps, and is being used by the National Football League (NFL) in the US.

Smart textiles are also available as consumer sportswear, which can monitor parameters such as heart rate and running statistics linking wirelessly to electronic devices such as iPhones, as with the Nike™ + products or smart phone android apps, as with the adidas Micoach system.

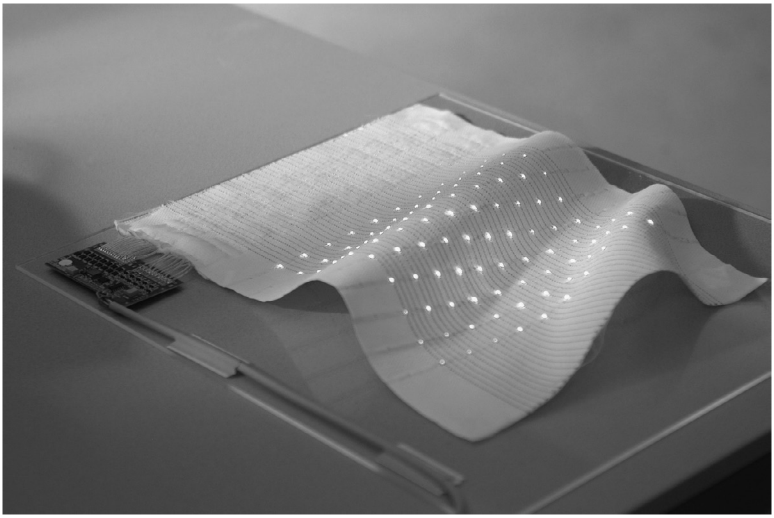
While much focus has been placed on monitoring applications and using textiles to gather information from the body, it is also possible to use smart textiles to provide therapeutic benefits to the wearer. Smart textiles are capable of providing heat to the body to treat conditions such as arthritis, muscle pain and spasm, joint stiffness or Raynauds Syndrome. Fabric heating systems are

15.5 SmartLife™ has developed softsensor™ systems aimed for the improvement of lifestyle. The HealthVest® is created with integrally knitted ECG electrodes, respiratory sensors and conductive pathways. (Image courtesy of Smartlife Technologies.)

developed by EXO^2 (http://www.exo2.co.uk/). The EXO^2/FabRoc® heating system delivers infrared heating to the affected areas, which are typically the knees, hips, lower back, hands and neck. The company also develops heated clothing for outdoor, equestrian and motorcycle use. Another company developing heated garments is Gerbing's Heated Clothing. This technology was originally designed for use on motorbikes with a 12 V power supply and they have extended their product range to be used with portable 7 V battery packs. They moved from integrating copper wires into garments to Microwire™ technology, using bundles of hundreds of microscopic stainless steel strands.

Wound care is one of the most lucrative medical device markets and there has been much effort in developing textiles to promote rapid healing of wounds in order to obtain functional and cosmetic results (Gupta *et al.*, 2010). Smart textiles can help to provide the optimum environment, such as optimum moisture levels and gas diffusion. A system for monitoring changes in pH and inflammatory proteins has been developed by Pasche *et al.* (2008), as part of the European BIOTEX project, with potential use in the supervision of skin grafts and ulcer treatments. Another EU funded project, Lidwine, focused on the development of multifunctional medical textiles to prevent and treat decubitus wounds. Target applications include an antibacterial textile for wound care, integrated with medication depots, including an active circulation support bandage with a contractile cuff. Textiles, given their flexible nature, have the advantage of being easy to apply to any location of the body. A thin and flexible luminous textile embroidery was developed by Selm *et al.* (2007), using plastic optical fibres. The textile diffuser has novel biomedical application in the field of cancer treatment, where the luminous embroideries are used to apply light energy to cancerous tissue during photodynamic therapy (Selm *et al.*, 2007). Philips are developing a phototherapy blanket, emitting blue light, to treat neonatal jaundice. At present, babies are placed beneath overhead lamps, whereas a soft blanket would be in close range with the baby's skin, which should improve the efficiency of the treatment. This approach also allows interaction with parents and caregivers, without interrupting the baby's treatment. Figure 15.6 shows the woven electronic platform developed by Philips, which integrates light emitters into a textile.

While electrodes may be integrated as detectors, another possibility is to use the electrodes to stimulate muscles. Electrodes for functional electrical stimulation (FES) have been integrated into fabrics, to provide actuation stimuli to muscles of the spinal cord of injured and stroke subjects, in order to generate or improve lost motor function, for example, for walking or hand gripping movements (Kirstein *et al.*, 2003). Electro-active polymers represent suitable candidate flexible components for the embedding of 'artificial muscle' functions into garments (Carpi and De Rossi, 2005). In the future, robotic and wearable technologies or smart fabrics could be combined to deliver therapeutic interventions (Bonato, 2010).



15.6 Philips Lumalive 'Woven electronics' fabric platform. (Image courtesy of Philips.)

15.5 Conclusions

The stages of treatment for most medical conditions include prevention, immediate care, rehabilitation and long-term support. Smart textiles have a role to play in each of these stages in treatment and prevention of illness. Integrating smart garments into our lives is a natural step, linking into our smart phones and interconnecting electronic devices. Through effective user feedback applications, there is potential to motivate individuals, promoting wellness and a healthy way of living. In the case of illness, smart garments can offer support to the medical community by providing a fuller picture of their patients' health and enable remote monitoring to reduce the frequency of clinical visits. In rehabilitation, a smart garment may help the patient take an active role in their recovery and prevent future relapse. In the future, smart textiles may have therapeutic functionalities, providing flexible and adaptable means of care.

15.6 References

Asada H H, Shaltis P, McCombie D and Reisner A (2010), 'Wearable blood pressure sensor and method of calibration', *US Patent 7674231*.

Asahina M, Yamanaka Y, Akaogi Y, Kuwabara S, Koyama Y and Hattori T (2008), 'Measurements of sweat response and skin vasomotor reflex for assessment of autonomic dysfunction in patients with diabetes', *J Diab Complic*, 22(4), 278–283.

Axisa F, Gehin C, Delhomme G, Collet C, Robin O and Dittmar A (2004), 'Wrist ambulatory monitoring system and smart glove for real time emotional, sensorial and physiological analysis', *Proceedings of the 26th Annual International Conference of the IEEE EMBS*, San Francisco, CA.

Barbaro M, Caboni A, Cosseddu P, Mattana G and A B (2010), 'Active devices based on organic semiconductors for wearable applications', *IEEE Trans Inf Technol Biomed*, 14(3), 758–766.

Benito-Lopez F, Coyle S, Byrne R and Diamond D (2010), ' "Sweat-on-a-Chip": analysing sweat in real time with disposable micro-devices', *Proceedings of the 9th Annual IEEE Conference on Sensors*, 1–4 November.

Bergmann J H M and McGregor A H (2011), 'Body-worn sensor design: what do patients and clinician's want?' *Ann Biomed Eng*, 39(9), 2299–2312.

Bonato P (2010), 'Wearable sensors and systems: from enabling technology to clinical applications', *IEEE Eng Med Biol Mag*, 29(3), 25–36.

Brisson G R, Boisvert P, Péronnet F, Parrault H, Boisvert D and Lafond J S (1991), 'A simple and disposable sweat collector', *Eur J Appl Physiol*, 63, 269–272.

Bronzino J D (2000), *The Biomedical Engineering Handbook*. Boca Raton, FL, CRC Press.

Carpi F and De Rossi D (2005), 'Electroactive polymer-based devices for e-textiles in biomedicine', *IEEE Trans Info Tech Biomed*, 9(3), 295–318.

Catrysse M, Puers R, Hertleer C, Van Langenhove L, Van Egmond, *et al.* (2003), 'Fabric sensors for the measurement of physiological parameters', *Transducers '03, 12th International Conference on Solid-State Sensors, Actuators and Microsystems*, Boston, MA.

Chen W, Bouwstra S, Bambang Oetomo S and Feijs L M G (2010), 'Intelligent design for neonatal monitoring with wearable sensors', in Somerset, V. S. (Ed.), *Intelligent and Biosensors*. InTech. pp. 1–24

Coyle S, Lau K, Moyna N, Diamond D, Di Francesco F, *et al.* (2010a), 'BIOTEX: Biosensing textiles for personalised healthcare management', *IEEE Trans Info Tech BioMed*, 14(2), 364–370.

Coyle S, Mitchell E, May G, O'Connor N E and Diamond D (2010b), 'Textile sensors for personalized feedback', *Proceedings of the ECIR 2010 Workshop on Information Access for Personal Media Archives*, Milton Keynes, UK.

Curto V F, Coyle S, Byrne R, Angelov N, Diamond D and Benito Lopez F (2012), 'Concept and development of an autonomous wearable micro-fluidic platform for real time pH sweat analysis', *Sens Actuat B*, DOI:10.1016/j.snb.2012.02.010 (in press).

D'Angelo L T, Weber S, Honda Y, Thiel T, Narbonneau F and Luth T C (2008), 'A system for respiratory motion detection using optical fibers embedded into textiles', *Proceedings of the Engineering in Medicine and Biology Society. EMBS 2008 30th Annual International Conference of the IEEE*.

De Rossi D and Veltink H (2010), 'Wearable technology for biomechanics: e-textile or micromechanical sensors?' *IEEE Eng Med Biol Mag*, May/June, 37–43.

Duquenoy P and Whitehouse D (2010), 'A 21st century ethical debate: pursuing perspectives on ambient intelligence', in: Duquenoy P, Zielinski C and Kimppa K (Eds.), *The Information Society: Emerging Landscapes*, New York, Springer. pp. 293–314.

Fagette P (1997), 'Tracking the historical development of biomedical engineering: the 1960s and 1970s', *IEEE Eng Med Biol Mag*, 16, 164–175.

Farina D, Lorrain T and Negro F (2010), 'High-density EMG E-textile systems for the control of active prostheses', *Proceedings of the 32nd Annual International Conference of the IEEE EMBS*, Buenos Aires, Argentina.

Finni T, Hu M, Kettunen P, Vilavuo T and Cheng S (2007), 'Measurement of EMG activity with textile electrodes embedded into clothing', *Physiol Meas*, 28, 1405–1419.

Gaetano Valenza A L, Scilingo E P and De Rossi D (2010), 'Towards a smart glove: arousal recognition based on textile Electrodermal Response', *Proceedings of the 32nd Annual International Conference of the IEEE EMBS*, Buenos Aires, Argentina, 31 August–3 September.

Gatzoulis L and Iakovidis I (2007), 'Wearable and portable e-Health systems: technological issues and opportunities for personalized care', *IEEE Eng Med Biol Mag*, 26(5), 51–56.

Gupta B, Agarwal R and Alam M S (2010), 'Textile-based smart wound dressings', *Ind J Fibre Text Res*, 35(2), 174–187.

Haider A and Solish N (2005), 'Focal hyperhidrosis: diagnosis and management', *Can Med Assoc J*, 172(1), 69–75.

Heilman K J and Porges S W (2007), 'Accuracy of the LifeShirt® (Vivometrics) in the detection of cardiac rhythms', *Biol Psych*, 75(3), 300–305.

Janata J (2009), *Principles of Chemical Sensors*, Second Edition, London, Springer.

Kappeler-Setz C, Schumm J, Kusserow M, Arnrich B and Tröster G (2010), 'Towards long-term monitoring of electrodermal activity in daily life', *Ubicomp 2010*.

Kirstein T, Lawrence M and Tröster G (2003), 'Functional electrical stimulation (FES) with smart textile electrodes', *International Workshop on a New Generation of Wearable Systems for E-Health*, Pisa, Italy.

Linz T, Gourmelon L and Langereis G (2007), 'Contactless EMG sensors embroidered onto textile', *Proceedings of the 4th International Workshop on Wearable and Implantable Body Sensor Networks*, Aachen, Germany.

Liu Y, Gorgutsa S, Santato C and Skorobogatiy M (2012), 'Flexible, solid electrolyte-based lithium battery composed of $LiFePO_4$ cathode and Li_4Ti5O_{12} anode for applications in smart textiles', *J Electrochem Soc*, 159(4), A349–A356.

Loriga G, Taccini N, Pacelli M and Paradiso R (2007), 'Flat knitted sensors for respiration monitoring', *IEEE Elect Mag*, Fall 2007, 5–8.

Lymberis A and Paradiso R (2008), 'Smart fabrics and interactive textile enabling wearable personal applications: RandD state of the art and future challenges', *Proceedings of the 30th International Conference of IEEE Engineering in Medicine and Biology Society*, Vancouver, BC.

Mattmann C, Amft O, Harms H, Clemens F and Tröster G (2007), 'Recognizing upper body postures using textile strain sensors', *Proceedings of the 11th International Symposium on Wearable Computers (ISWC07*), Boston, MA.

Mattmann C, Clemens F and Tröster G (2008), 'Sensor for measuring strain in textile', *Sensors*, 8(6), 3719–3732.

McCann J, Hurford R and Martin A (2005), 'A design process for the development of innovative smart clothing that addresses end-user needs from technical, functional, aesthetic and cultural view points', *Wearable Computers, 2005. Proceedings of the 9th IEEE International Symposium*, 18–21 October, pp. 70–77.

Merritt C R, Nagle H T and Grant E (2009), 'Fabric-based active electrode design and fabrication for health monitoring clothing', *IEEE Trans Info Tech BioMed*, 13(2), 274–280.

Mitchell E, Coyle S, Ward T, O'Connor N E and Diamond D (2010), 'Breathing feedback system with wearable textile sensors', *Body Sensor Networks (BSN 2010*), 7–9 June, Biopolis, Singapore.

Paradiso R, Belloc C, Loriga G and Taccini N (2005a), 'Wearable healthcare systems, new frontiers of e-textile', in: Nugent C D, Mccullagh P J, Mcadams E T and Lymberis A

(Eds.), *Studies in Health Technology and Informatics*, vol. 117, *Personalised Health Management Systems: The Integration of Innovative Sensing, Textile, Information and Communication Technologies*.

Paradiso R, Loriga G and Taccini N (2005b), 'A wearable healthcare system based on knitted integrated sensors', *IEEE Trans Inf Technol Biomed*, 9(3), 337–344.

Paradiso R and DeRossi D (2006), 'Advances in textile technologies for unobtrusive monitoring of vital parameters and movements', *Proceedings of the 28th IEEE EMBS Annual International Conference*, New York, 30 August–3 September, pp. 392–395.

Pasche S, Angeloni S, Ischer R, Liley M, Luprano J and Voirin G (2008), 'Wearable biosensors for monitoring wound healing', *Adv Sci Tech*, 57, 80–87.

Perry J T, Kellog S, Vaidya S M, Jong-Hoon Y, Hesham A and Sharif H (2009), 'Survey and evaluation of real-time fall detection approaches', *Proceedings of the 6th International Symposium on High-Capacity Optical Networks and Enabling Technologies (HONET) 2009*.

Pickering T G, Hall J E, Appel L J, Falkner, B E, Graves J, *et al.* (2005), 'Recommendations for blood pressure measurement in humans and experimental animals', *Hypertension*, 45, 142–161.

Poh M Z, Swenson N C and Picard R W (2010), 'A wearable sensor for unobtrusive, long-term assessment of electrodermal activity', *IEEE Trans Biomed Eng*, 57(5), 1243–1252.

Reisner A, Shaltis P A, McCombie D and Asada H H (2008), 'Utility of the photoplethysmogram in circulatory monitoring', *Anesthesiology*, 108(5), 950–958.

Rothmaier M, Selm B, Spichtig S, Haensse D and Wolf M (2008), 'Photonic textiles for pulse oximetry', *Opt Exp*, 16 12 973–12 986.

Rovira Carlos W T, McCoy A, Coyle S, Corcoran B, Stroiescu F, *et al.* (2011), 'Web-based wearable sensor streaming for respiratory monitoring applications', *Proceedings of the IEEE Sensors*, Limerick, Ireland.

Salvo P, Di Francesco F, Costanzo D, Ferrari C, Trivella M G and De Rossi D (2010), 'A wearable sensor for measuring sweat rate', *IEEE Sens J*, 10(10), 1557–1558.

Sarabdeen J (2012), 'Legal issues in e-healthcare systems', in: Wafta M K (Ed.), *E-Healthcare Systems and Wireless Communications: Current and Future Challenges*. IGI Global.

Schwarz A, Van Langenhove L, Guermonprez P and Deguillemont D (2010) 'A roadmap on smart textiles', *Text Prog*, 42(2), 99–180.

Selm B, Rothmaier M, Camenzind M, Khan T and Walt H (2007), 'Novel flexible light diffuser and irradiation properties for photodynamic therapy', *J Biomed Opt*, 12, 034024.

Selm B, Gürel E A, Rothmaier M, Rossi R M and Scherer L J (2010), 'Polymeric optical fiber fabrics for illumination and sensorial applications in textiles', *J Intell Mat Syst Struct*, 21, 1061–1071.

Shirreffs S M and Maughan R J (1997), 'Whole body sweat collection in humans: an improved method with preliminary data on electrolyte content', *J Appl Physiol*, 82, 336–341.

Solà J O C and Krauss J (2007), 'On the reliability of pulse oximetry at the sternum', *Proceedings of the 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Lyon, France.

Street L (2008), *Introduction to Biomedical Engineering Technology*. Boca Raton, FL, CRC Press.

Tatara N, Koizumi H, Mino S, Hayashida S, Aihara K, *et al.* (2007), 'A novel blood pressure monitoring device for ubiquitous healthcare services', *Proceedings of the 29th Annual International Conference of the IEEE EMBS*, Lyon, France.

Tognetti A, Lorussi F, Tesconi M, Bartalesi R, Zupone G and De Rossi D (2005), 'Wearable kinesthetic systems for capturing and classifying body posture and gesture', *Proceedings of the Engineering in Medicine and Biology 27th Annual Conference*, Shanghai, China.

Trafton A (2009), 'Wearable blood pressure sensor offers 24/7 continuous monitoring. Device could help diagnose hypertension, heart disease', *MITnews*, available from http://web.mit.edu/newsoffice/2009/blood-pressure-tt0408.html.

Vaughan J and Scully P J (2008), 'Optical sensing for perspiration', *Photon 08: Optics and Photonics Conference*, Heriot Watt University, Edinburgh. Bristol, Institute of Physics Publishing.

Whitehouse D and Duquenoy P (2011), 'e-Health and ethics: theory, teaching, and practice', (Festschrift in honour of Bradley), in: Haftor D and Mirijamdotter A (Eds.), *Information and Communication Technologies, Society and Human Beings: Theory and Framework*. Hershey, PA, IGI Global.

World Health Organisation (2007) *WHO Global Report on Falls Prevention in Older Age*.

Xu P J, Zhanga H and Tao X M (2008), 'Textile-structured electrodes for electrocardiogram', *Text Prog*, 40(4), 183–213.

Yang Y L, Chuang M C, Lou S L and Wang, J (2010), 'Thick-film textile-based amperometric sensors and biosensors', *Analyst*, 135(6), 1230–1234.

Yu X (2008), 'Approaches and principles of fall detection for elderly and patient', *HEALTHCOM 2008*.