Smart textiles for healthcare: applications and technologies

Viktorija Mečņika[1] Ms.sc.; **Melanie Hoerr**[2] Dipl.-Ing.;
Ivars Krieviņš[1] Assoc.prof. Dr.sc.ing.; **Anne Schwarz**[2] Dr.sc.ing.
Institute of Textile Technology and Design of Riga Technical University, Latvia[1];
Institut fuer Textiltechnik of RWTH Aachen University, Germany[2]
viktorija.mecnika@rtu.lv, ivars.krievins@rtu.lv[1]; melanie.hoerr@ ita.rwth-aachen.de,
anne.schwarz@ita.rwth-aachen.de[2]

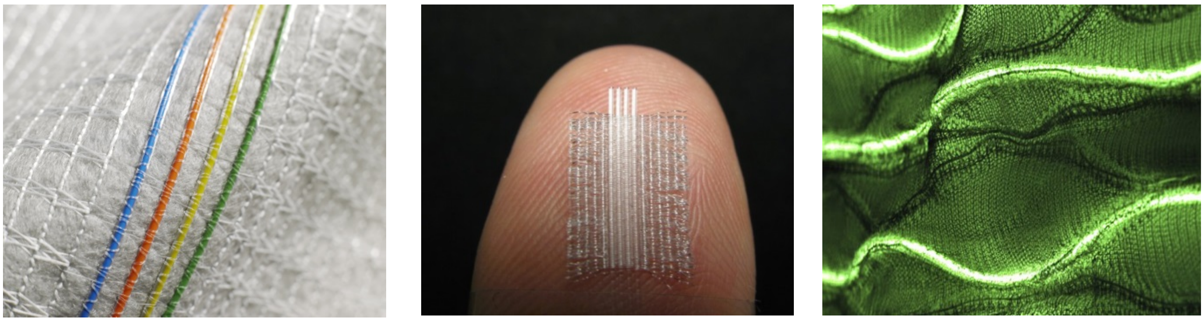
Abstract: Smart textiles are considered to be a new niche for products with great potentials on the textile and apparel market. Generally, smart textiles are referred as textile products with additional value, i.e. they have the common properties of textiles, but insure additional functions, providing attractive solutions for a wide range of application fields, such as healthcare, clothing for protection and sports and technical textiles for automotive industry. However, manufacturing of smart textile products demands a complex and innovative technological approach, combing conventional textile manufacturing technologies as weaving, knitting and embroidery with technologies originating from the electronic sphere, such as coating, lithography and ink-jet printing. Thus, functionalization of textiles may be processed at different levels, i.e. from fibers till fabric or even ready-made clothing. Understanding of drivers, state-of the-art and tendencies in smart textiles ensures further efficient development technology and its interaction with manufactures and consumers. The paper explores and systematically describes applications of smart textiles for healthcare with sensing and actuating functions and introduces to the main principles of technology for textile sensor manufacturing.

Keywords: smart textiles for healthcare, textile sensors, wearable technology, joining technology.

Introduction

Textile and apparel market represents one of the significant segments in the world trade and product manufacturing. Traditionally the textile industry is referred to production of fibres, yarns, fabrics and textile goods. Within technology development, growth of competition on the market and changes in the society, new solutions are required and so that applications of textiles are increasingly expanding. Keys for innovations in textiles are in the focus of the multidisciplinary research in engineering and medicine due to such unique features of textiles as lightweight, flexibility, dimensional variability and opportunities to achieve specific properties through structure and surface modification at different levels. There are many examples of successful efforts in improvement of physical and chemical properties of textiles and extension of their functionality. Moreover, in recent decades a significant breakthrough has been achieved in exploring and enhancing capabilities of textiles to response for environmental stimuli. Such textiles are identified as smart or intelligent, and vary in their nature, technology solutions and applications. Smart textiles possess the properties of conventional textile materials and carry additive functional values. Those are usually associated with sensing and interaction performance. Sometimes such products are aligned with wearable electronics, which is often an indispensable part of intelligent textiles (Van den Kirboom, Byluppala, 2011, Kirstein, 2013).

Smart textiles find applications and have outstanding outlooks almost in every sphere of human activities. Many research projects are dedicated to exploring and developing smart textiles for medicine and healthcare. Use of such smart textile materials vary from *in-vitro* applications to *in-vivo* use as an asset in everyday activities and accomplishing such functions as philological monitoring and communication with environment. Another field of smart textile application is technical textiles for monitoring of structural health, automotive, civil, geotechnical and other engineering industries. Besides high functionality, some smart and intelligent textiles have outstanding aesthetic values and find applications in fashion and design.



(a) (b) (c)

Figure 1. Examples of optical fibre applications in smart textiles for environmental engineering (Dijcker, Van Der Wijk, 2011), (a), medicine (Rothmaier, Selm, 2008), (b) and design (Image: Optical fibre…, 2013), (c)

Figure 1 demonstrates an example of optical fibre applications in engineering, medicine and design. The first picture displays a sensor integrated into geotextiles for temperature and strain measurements (a) (Dijcker, Van Der Wijk, 2011). The second one represents a woven sensor for pulse oximetry assessment (Rothmaier, Selm, 2008). The last picture displays optical fibre use for decorative purposes (Image: Optical fibre…, 2013). It has been proposed that smart textiles can be characterized by their functionality, which often refers to the application field, and integration level of the 'smart compound' (Weber, Adler, 2009, Steffen, Adler, 2013, Catrysse, Pirotte, 2007, Textilien und textile..., 2012). Solutions for manufacturing smart textiles are generally based on such textile production technologies as weaving, knitting and embroidery, and involve textile materials and structures that respond to electrical, mechanical, optical, chemical, thermal or magnetic stimuli (Cherenack, van Peterson, (2012). Quite often those incorporate several technological methods and involve such processing techniques as lithography, inkjet-printing and surface modification in order to achieve a high-performance product. Such combined approach is referred as a joining technology. It offers a broader range of scenarios that find applications in the development of efficient textile-based sensors and insurance of interconnecttions of electronic and textile compounds. Although overall smart textiles still are associated with the research and development sphere, those are resolutely gain relevance in practical use, and experimental manufacturing technologies are being transferred to the industry. Above special and high-technological applications of such textiles, there are already products available also for personal use. One of the most common examples of smart textiles solutions on the market are textile electrodes for heart rate measurements during sports activity.

Despite a variety of smart textiles applications, a significant role has the research that focuses on intelligent systems for healthcare and medicine. The main drivers encouraging development of this segment are socially-demographical situation in Europe and other developed countries, high competition on the textile market and new scopes of available engineering, information and communications technologies. Aging of the population, leads to increasing number of geriatric patients and thereby demands more investments in nursing and medical sectors. On the other hand, the textile and clothing sector is characterized by extreme competition and the micro-segment of smart textiles is one of promising niches for business development in EU based on the R&D platform and new technology transfer from research institutions to industry. This results in investigation and production of wearable textile-based systems for healthcare and compounds for Ambient Assisted Living (AAL) environment. The first attempts to manufacture biomonitoring clothing have already started over a decade, and there are a great number of reports published on investigations of separate compound and complex systems development.

Methodology

This study makes an introduction to the sphere of smart textiles for healthcare and further focuses on biomedical applications that are based on the sensorial textiles compounds. Further, the paper systematically describes the main types of such developments and most common technological solutions.

Results and Discussion

Applications of Smart Textiles for Healthcare

Smart textiles for healthcare include textile sensors, actuators and wearable electronics systems embedded into textiles that enable registration and transmission of physiological data, and wireless communication between the wearer and the ‘operator’, for example, patient and medical personal. Such systems ensure patients’ mobility, thereby providing a higher level of psycho-physiological comfort, especially when a long-term bio-monitoring is required (Kirstein, 2013, Catrysse, Pirotte, 2007; Textilien und textile..., 2012; Cherenack, van Peterson, 2012; Chan, Esteve, 2012; Alemdar, Ersoy, 2010; Schwarz, van Langenhove, 2010).

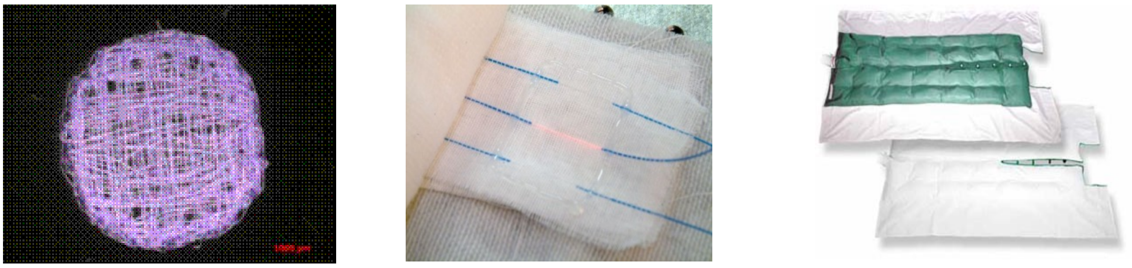
Generally, applications of smart textiles for medicine and healthcare vary from the surgical applications of single yarns to complex wearable and axillary systems for personalized healthcare. There is no still classification smart textile for these applications, but initially those can be described referring to commonly distinguished groups in conventional medical textiles. Of course, due to new functions, several new categories must be highlighted. Those are textile drug-release systems, textiles with biometric performance and active textiles for therapy and wellness. In the Table 1 are summarized main applications fields of smart medical textiles (Rigby, Anand, 2000, Bartels, 2011, Van Langenhove, 2007, Vargas, 2005).

Table 1

Applications of smart textiles for medicine and healthcare

Application	**In vitro**	**In vivo**
Surgery	Bandages Wound-care	Sutures Soft-tissues Orthopaedic implants Cardiovascular implants
Hygiene	Uniform for medical personal Hospital textiles	-
Drug-release systems	Smart bandages and plasters	-
Bio-monitoring	Cardiovascular and haemodynamic activity Neural activity Muscle activity and kinematics Respiratory activity Thermoregulation	-
Therapy and wellness	Electrical stimulation therapy Physiotherapy Auxiliary systems Active thermoregulation systems	-

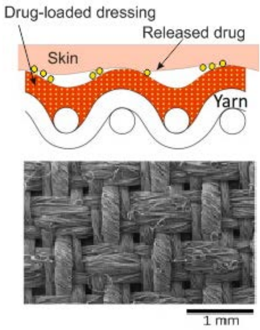
Traditionally medical textiles find applications in surgery and hygiene.



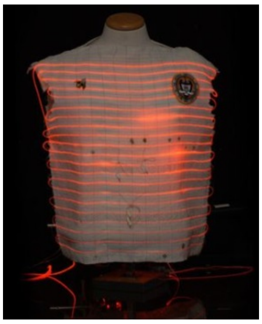
(a) (b) (c)

Figure 2. Embroidered scaffold (Rotsch, Hanus, 2009) (a); wound dressing with pH sensor (b) (Pasche, Schyrr, 2013); warming blanket for decubitus prophylaxis (Image: Warming Blanket… , 2013) (c)

Within new achievements in material science and textile related disciplines, new advanced products referred to smart medical textiles are entering this sphere.Specifically for implantable surgical materials, a real breakthrough has been gained in tissue engineering using textile technology that ensures two- and three-dimensional structure development. Such implantable structures and compounds encourage cell distribution and adhesion in the body. Moreover, those can possess outstanding mechanical properties and ensure opportunity to create different geometrical structures. Figure 2 (a) displays a sample of a scaffold developed by chemical embroidery in TITV Greiz (Rotsch, Hanus, 2009).



(a)



(b)

(c)

Figure 3. Medical textile with a lubricating drug-delivery dressing (Gerhardt, Lottenbach, 2013) (a); Wearable Motherboard^{TM} for vital signs monitoring (Image: Wearable Motherboard^{TM} , 2013; Park, S., Jayaraman, 2001) (b); Philips phototherapy blanket for new-borns' jaundice treatment (Lorussi, Scillingo, 2005) (c)

Non-implantable or *in vivo* surgical smart textiles can be also characterized by a specific two- or three-dimensional structure and/or additional functional compounds. Those could be miniature fibre-based biosensors that monitor or improve the healing process. For instance, there are already several scenarios are suggested to insure pH level monitoring for wound and burn management for assessment of biochemical changes in the wound environment (Figure 2 (b)) (Pasche, Schyrr, 2013; Scharp, 2013).

A relatively new category of smart medical textiles is textile-based drug delivery systems (Figure 3 (a)) (Van Langenhove, 2007; Gerhardt, Lottenbach, 2013). In some cases, transdermal drug delivery can be a good alternative to traditional pills and medicaments in such situations when it is necessary to reduce the effect on stomach and intestinal tract, or medicaments lose their activity. Moreover, transdermal drug delivery is a solution when oral administration is not possible or difficult (Van Langenhove, 2007). The fusion of textile and biotechnology with chemistry and pharmacy studies can offer a variety of scenarios for drug delivery system development. At present there are different delivery methods are developed. In those, textiles can have functions from a carrier or a forming layer, e.g. transdermal patches, till advanced systems with controlled drug-release.

Above that, smart materials find applications in hospital textiles and clothing for medical personal. Additional functionality of such textiles can be obtained by different approaches according to specific applications. For this type of medical textiles though, most solutions are brought by functional textiles. For hospital textiles, those commonly are textile materials with antimicrobial and antibacterial properties or low friction coating. Clothing for medical personal is also made of functional textiles that insure efficient moisture transport and biological protection. Nevertheless, conductive textile materials are more often used in manufacturing of heating textiles that find applications in blankets for operating rooms (Figure 2(c)) (Image: Warming Blanket… , 2013). Above that, conductive textile materials can be an asset in improvement of distanced communication between medical personal and patients through wearable technologies integrated into clothing. Smart textiles also offer solution for decubitus prophylaxis and related health disorders that are a significant problem in the hospital environment. At present, there are already a number of developments that assist in managing these problems through innovative and smart textile solutions. Namely, those can be implemented by stimulating blood flow in sensitive areas via textile-based sensors and systems, optimizing and controlling moisture management via textile sensors (Lenting, 2012).

First most known attempts in textile sensor development were reported over a decade ago within such research projects as *Wearable Motherboard™* by Georgia Tech, and such EU projects *Wealthy* and *My Heart* (Fig.3 (b)) (Image: Wearable Motherboard™ , 2013; Park, S., Jayaraman, 2001; Paradiso, Loriga, 2005; Harris, Habetha, 2007). At present, there is a great variety of textile sensors and complete systems for assessment of physiological and biochemical processes (Table 1).

Besides biomonitoring functions, smart sensors can assist in such prophylactic and therapeutic arrangements as muscle electrical stimulation and posture monitoring (Gniotek, Frydrysiak, 2011; Keller, Kuhn, 2008; Dunne, Walsh, 2006; Dunne, Walsh, 2007). For such applications as photo- and photodynamic therapy, textiles can be carrier materials and textile manufacturing technology can be a mean of a product manufacturing. There are a number of such developments for pain relief and jaundice treatment that are based on light emitting diode (LED) and optical fibre technology (Figure 3(c)). For these applications, textiles ensure development of wearable and portable flexible systems with friendly interface. Moreover, textile technology is an advantageous approach to manufacture textile diffusers with different dimensions and structure. Electro-conductive materials are also used for active thermoregulation system development. Those can be integrated into clothing or into garment items to ensure external temperature regulation in clothing systems or be an asset in infra-red pain management (Rantanen, Alfthan, 2000; Product catalog of TherMedic…, 2013).

Textile Sensors in Smart Textiles for Healthcare

As it has been mentioned above, textile sensors for physiological assessment and therapy purposes vary in their functions and applications, materials and technology solutions, and integration level into textiles. According to their general working principles, those can be physical, biochemical and optical transducers. Further, those can be divided into several categories according to their integration level into textile structure. This is mostly defined by the chosen technology approach. According to the literature review, four general sensor structure categories were defined:

- fibre-based, when a sensor is a single yarn;
- textile-structured, when all compounds of a transducer are textile materials;
- textile-based, when textiles are a substrate or another non-sensitive, but inseparable compound of a transducer;
- textile-integrated, when textiles carry the function of a carrier.

Above that, textile sensors can be characterized by their functions, measurement units and application. Variations in solution implementation approach ensure application of the same technology for different purposes. For example, optical fibre technology offers scenarios for such criteria assessment as temperature, moisture, blood oxygenation and sweat pH level, respiration rate and movement. Thus, in order to present an overview of available solutions for healthcare, those were described according to their sensory functions. Often smart sensors require a complex implementation approach by joining technology in order to achieve a better performance. Although textile sensors differ in their structure, the main compounds, on which is based the working principle, are a substrate and, sensing or active materials. Structures of sensors implemented by such technologies as coating, thin films, lithography and inkjet-printing, can incorporate also such functional elements as a capping or encapsulation layer that protect the sensitive compounds (Sibinski, Jakubowska, 2010).

Textile electrodes

Textile electrodes can be divided into passive and active ones [16]. In both cases, their operation principle though is similar to conventional electrodes working principles. Passive electrodes can be defined as textile sensors capable of electrical signal acquisition. They find most applications in registration of cardiac and muscle activity through detecting electrical potentials generated by the heart and muscles. They find applications for heartbeat estimation, heart rate variability (HRV) analysis, electrocardiography (ECG) and electromyography recording. There are also investigations in textile electrode development for assessment of electrical activity of the brain. These electrodes measure voltage fluctuations that result from ionic current flows within the neurons and are an alternative solution for conventional electroencephalography electrodes. Above that, passive textile electrodes can be used in assessment of galvanic skin response. Those change their conductivity according to the electrolyte saturation in the sweat produced from the skin surface. Such electrodes find applications in smart textiles and clothing for continuous wireless biomonitoring and biofeedback wearable systems. Active textile electrodes for smart medical textiles can be referred to electrodes for transcutaneous electrical stimulation. Such electrodes transduce the applied electrical current to a tissue probe on a skin surface in order to activate the targeted nerve cells, skin receptors or other sensory and motor units of the body or achieve pain relief through nerve electrical stimulation (Keller, Kuhn, 2008; Li, Au, 2009).

The most common used materials for the sensor implementation are conductive textile materials that can be yarns that ensure fabricating of textile electrodes via such conventional textile manufacturing technologies as weaving, knitting and embroidery. Another approaches offer solutions implemented via inkjet and screen printing, and such thin film technologies as sol-gel and sputtering methods (Xie, Yang, 2013; Rattfält, Björefors, 2013; Cho, Jeong, 2011). The textile electrodes fabricated by the mentioned conventional techniques demonstrate though higher efficiency in performance and usage (washing).

Temperature sensors

Another crucial parameter in health monitoring is body temperature. It results from the balance between the heat production and heat loss and reflects the processes of the chemical and physical thermoregulation cohered with activity of other organ systems, e.g. endocrine and neural systems. For medical assessment, the most informative and significant parameter is core temperature, which is the constant temperature in the deeper parts of the body and in the proximal extremity portions. Another criterion is shell temperature, which is measured on the skin surface and at the hands and feet to approach the room temperature of 19 ^{o} C in a person standing in a cold room for hours (Li, Yang, 2012).

Temperature sensors based on smart textiles technology can provide evaluation of temperature changes on skin surfaces and in the near-body environment. These data can be used for such applications as physiological assessment, control and improvement of the patient's comfort, and monitoring of wound healing. Textile manufacturing and engineering technologies offer solutions for fabrication fibre-based or single yarn, woven, knitted, embroidered and printed textile sensors for temperature estimation (8) (9). By their operation principle the reported temperature sensors are designed like thermocouples, resistive or strain, semiconductive and optical sensors.

Initially thermocouple can be referred as the simplest solution for temperature sensor implementation due to its structure. Those consists of two dissimilar metal materials coupled in one point and a voltage related to the temperature difference is produced the junction between the metals. The achieved data can be further converted into an output temperature signal by the electronic circuit. Resistive or strain temperature sensor works as the resistance temperature detector (RTD). The working principle of such sensors is based on the changes of metal electrical resistance related to the temperature. Both types of the mentioned temperature sensors are commonly fabricated from conductive yarns or with application of metal monofilament wire. Semiconductive sensors are polymer- based and temperature signal is achieved according to the spreading resistance analysis of semiconductors. Another type of a temperature sensor is a fiber Bragg grating (FBG)-based sensor, which is a sensitive optical material reflecting particular wavelength of light and transmitting the others. Fibre engineering and coating technology inspire development of single yarn miniature sensors based on thermosensitive polymers and carbon nanotubes and FBGs-based sensors.

Respiration rate sensors

In physiology, respiration is defined as the process of taking up oxygen and removing carbon dioxide from cells in the body (Li, Yang, 2012). This is a two stage biochemical process resulting in gas exchange and cellular respiration. Breathing is characterized by respiration rate (RR, breaths per minute). Breathing that consists of inhalation and exhalation activity is a part of respiration and coheres with abdominal and chest movements. Strain sensors ensure efficient estimation of this motion activity and then the acquired data can be used for RR evaluation. Optical fibres are one of the most used materials for these purposes due to relative simplicity of the measurement approach and processing of optical fibres with such technologies as weaving and embroidery (Park, Jayaraman, 2001; Narbonneau, De Jonckheere, 2010).

Although respiration rate has limited applications in respiratory dysfunction assessment, this parameter is often crucial in telemetric monitoring during specific clinical assessment procedures, sleep monitoring and a number of respiratory disorders. Textile sensors for RR estimation also find a number of applications in protective and combat clothing, smart textiles for prevention of sudden infant death syndrome (SIDS), and monitoring of vital signs for geriatric or disabled patients (Cherenack, van Peterson, 2012, Chan, Esteve, 2012; Narbonneau, De Jonckheere, 2010; Witt, Schukar, 2013). For these purposes, breathing is first of all an indicator of normal physical activity. Above that, this parameter along with cardiovascular parameters can be also an important criterion in sports physiology in order of planning an efficient training without risk for health.

Textile sensors for kinematic analysis

Besides registration of physiological parameters, textile materials can assist in kinematic analysis, monitoring of body motion and positioning. These criteria are significant in rehabilitation and assessment of skeletal system during therapy treatment and diagnostics with application of optical fibres, piezoelectric materials and elastomers (Dunne, Walsh, 2006, Dunne, Walsh, 2007; De Rossi, Bartalesi, 2006; Fereira, Rocha, 2013). Such approaches ensure wearable textile-integrated solutions for long-lasting monitoring of gait, posture, particular body units and joints, and general positioning or movement activity of a patient. Acquired data can be processed and used for real-time remote image capturing without use of camera application or complicated inertial sensor systems. Besides wearable sensors, there are sensors for motion capturing for such applications as Ambient Assisted Living (AAS) and sleep monitoring (Lauterbach, Steinhage, 2013; Lauterbach, Steinhage, 2013). Solution for such applications can be ensured by capacitive textile sensors and implemented according to a variety of scenarios using conductive textiles and piezoelectric materials.

Humidity sensors

Humidity is a crucial criterion in many philological and biological processes, and can significantly influence human's health. Initially moisture can be referred as absolute humidity that indicates the actual amount of vapour. Relative humidity (RH) implies the percentage of the vapour amount in the air at prescribed temperature that is compared to the amount of vapour, which could hold in the air by this temperature. Capacitive humidity sensors consist of two electrodes and a dielectric placed between the electrodes. RH values are determined according to the capacitance changes of the dielectric constant, which is the relative humidity and temperature of the dielectric. Thus, the main requirement to the dielectric material is hydroscopicity, i.e. easy absorption of vapour in the environment. The operation principle of resistive humidity sensors is based on measuring the changes in electrical impedance in the hydroscopic medium. The hygroscopic material absorbs water and ionic functional groups are dissociated, resulting in an increase in conductivity. Thus, as the humidity increases, the resistance of the material decreases (Chen, Lu, 2005). Both described working principles of conventional capacitive and resistive humidity sensors can be transferred to textiles via different implementation scenarios. Efficient measurements of relative humidity usually require a complex approach by joining such technologies as weaving, embroidery, fibre coating, inkjet-printing and lithography (Pereira, Silva, 2011; Rumpf, 2008; Weremeczuk, Tarapata, 2012; Nocke, Schroeter, 2012). The choice of the most appropriate approach is determined by the chosen sensor structure, materials and applications. Initially textiles can be successfully used as a vapour or moisture absorbing substrate material due to their physical and chemical characteristics. Moreover, conductive textiles are a good candidate for implementation of sensor electrodes.

At present, there are found several approaches of humidity sensor development via smart textile technology for such healthcare applications as ulcer prevention, monitoring of sweat rate and moisture in wounds. A research team from Spain offers a fully textile moisture sensor for bed-rest patients developed with conductive yarns and metal monofilaments by weaving and pressing (Pereira, Silva, 2011). Researchers from the Warsaw University of Technology demonstrated another approach of sensor development by joining inkjet-printing and coating technology. Sensor electrodes were inkjet-printed directly on textiles and then coated with a vapour sorption layer (Weremeczuk, Tarapata, 2012). Conolly et al. used also printing technology to develop a moisture monitoring system with textile integrated sensors for wound healing assessment (Nocke, Schroeter, 2012). Another scenario for textile humidity sensor was realized. in the frames of EU *Biotex* project. They have developed a textile sandwich-structured capacitive sensor for sweat rate monitoring (Moriss, Coyle , 2009; Coyle, Morris, 2012).

Sensors for pH level estimation

The pH level is one the important indicators in assessment of biochemical processes in physiology and is regulated by acid-base homeostasis. The pH level is a crucial parameter in assessment of wound healing processes and in sweat monitoring. Modern textile and engineering technologies offer several scenarios to develop such a sensor that ensures continuous pH monitoring in real-time. Despite the variety of developments, there are found several key scenarios for sensor implementation described in the literature (Pasche, Schyrr, 2013; Moriss, Coyle , 2009; Coyle, Morris, 2012; Caldara, Colleoni, 2012; Vincenzini, Rossi, 2008; Van der Schueren, De Clerck, 2013).

One is based on application of such halochromic materials as pH-sensitive dyes and hydrogels and further colorimetric analysis. Such approach to measure sweat pH based on a textile based platform was described by Coyle et al. and Caldara et al. (Moriss, Coyle , 2009; Coyle, Morris, 2012; Caldara, Colleoni, 2012).

The textiles function for sweat collection and storage. A pH-sensitive coating immobilised on the fabric performed as a pH environment indicator and a biased LED performed a quantified sweat analysis. Another solution is integration of optical fibres with pH-sensitive coating into wound dressing (Pasche, Schyrr, 2013; Vincenzini, Rossi, 2008).

Another approach to assess pH range changes in wounds is based on impedance measurements. Nocke et al. suggested a scenario for an impedimetric single yarn sensor (Nocke, Schroeter, 2012). The sensor consists of a two monofimentary gold electrodes and a pH-sensitive layer. The inner electrode was covered a pH-sensitive hydrogel and the outer electrode was enwinded around the inner one.

Pulse oximetry sensor

Pulse oximetry is a non-invasive technique for estimation of the arterial oxygen saturation (SpO_2) in the studied biological tissue. Pulse oximeters measure the light absorption of oxygenated and deoxygenated haemoglobin at two different wavelengths in the near-infrared spectrum. Pulse oximetry finds application in such clinical applications as emergency and recovery rooms, intensive care and during anaesthesia (Rothmaier, Selm, 2008; Zysset, Nasseri, 2013; De Jockkheer, Jeanne, 2007; De Jockkheer, Narbonneau, 2008).

Although smart textile technology has not been yet that much explored in comparison with development of textile electrodes or other textile sensors, there are already offered solutions that are initially based on two scenarios. Zysset et al. have demonstrated a scenario is based on application of miniaturized electronics conventionally processed and integrated into textiles. Miniature LEDs and photodiodes (PDs) were placed on flexible plastic stripes that were woven into a fabric with conductive yarns, which ensure electrical interconnection between the incorporated compounds (Zysset, Nasseri, 2013). Another approach with application of optical fibre technology has been suggested in the research project Ofseth and a research team from Switzerland. In the frames of the former investigations, blended optical fibres were used to measure blood oxygenation (Zysset, Nasseri, 2013; De Jockkheer, Jeanne, 2007). Rothmaier et al. have offered three options to develop a SpO_2 sensor with weaving and embroidery two techniques using poly(methyl methacrylate) plastic optical fibres (PMMA POF) as sensing material and polyester fibres as the supporting material (De Jockkheer, Narbonneau, 2008).

Conclusions

Smart textiles find variety of applications and possess sensing and actuating functions that can be efficiently used in medicine, engineering and fashion. Smart textiles for the former use are one of the most important niches in the R&D sphere due to the socially-economic and technological drivers. Such textiles offer advanced solutions for smart clothing and textiles for sensing and actuating, protective wear, ambient assisted living, hospitals and surgery. Those have potentials to support healing processes, improve safety, comfort and living of patients ensuring their mobility in a friendly way.

There are already a great number of offered solutions and scenarios for manufacturing textile biosensors, but mostly those are still at the prototyping stage. Some products are already accepted by the industry and introduced to the market, but the process of development technology transfer to manufacturing is burden due to such factors as initially high costs of fabrication, and commercial introduction and use. The first step to overcome these technical, strategic and socially-economic barriers is prototyping technology alteration to mass production. This solution would lead consequently to the cost reduction and make the price of smart products more competitive and attractive in comparison with their parent items.

Technology and material solutions incorporate fibre, textile and electronics manufacturing technology with application of materials with electrical, chemical, mechanical, thermal and optical reaction. At present from the whole variety of textile sensors and actuators for healthcare, textile electrodes are those that are mostly commercially introduced due to the availability of the materials and well-developed technological approach. Optics technology is also often addressed to ensure sensing and actuating within textile products and interfaces.

Bibliography

1. Alemdar, H., Ersoy, C. (2010) Wireless Sensor Networks for Healthcare: A Survey. Computer Networks, Vol.54, pp.2688-2710
2. Bartels T.V. (2011). Handbook of Medical Textiles, Cambridge, Woodhead Publishing, pp.1-37, 173-197, 295-312
3. Caldara M., Colleoni C., Guido E. et al. (2012). Development of a Textil-Optoelectronic pH Meter Based on Hybrid Xerogel doped with Methyl Red. *Sensors and Actuators B: Chemical*, Vol. 171-172, pp. 1013-1021
4. Catrysse M., Pirotte F. (2007). The Use of Electronics in Medical Textiles. In: *Smart Textiles Medicine and healthcare. Materials, Systems and Applications.* Cambridge, Woodhead Publishing, p. 88-104
5. Chan M., Esteve D., Fourniols J.-Y. et al. (2012). Smart Wearable Systems: Current Status and Future Challenges. *Artificial Intelligence in Medicine*, Vol.56, pp.137-156
6. Chen Z., Lu C. (2005). Humidity Sensors: A Review of Materials and Mechanisms, *Sensor Letters*, Vol. 3, pp. 274-295.
7. Cherenack K., van Peterson L. (2012). Smart Textiles: Challenges and Opportunities. *Journal of Applied Physics*, Vol.112, pp. 1-14
8. Cho G., Jeong K., Paik M.J. et al. (2011). Performance Evaluation of Textile-Based Electrodes and Motion Sensors for Smart Clothing. *IEEE Sensors Journal*, Vol. 11 (12), pp.3183-3192
9. Coyle S., Morris D., Lau,K.-T. et al. *Textile Sensors to Measure Sweat pH and Sweat-Rate During Exercise* [online] [27.10.12] Availble at: http://doras.dcu.ie/3636/1/Coyle_pervasive2009.pdf
10. De Jockkheer J., Jeanne M., Grillet A. et al. (2007). OFSETH: Optical Fiber Embedded into Technical Textile for Healthcare, an Efficient Way to Monitor Patient Under Magnetic Resonance Imaging, In: *Proceedings of the 29th Annual International Conference of IEEE EMMBS*, Lyon, France, pp.3950-3953
11. De Jockkheer J., Narbonneau F., Kniet, D. et al. (2008). Optical Fibre Sensors Embedded into Technical Textile for a Continuous Monitoring of Patients under Magnetic Resonance Imaging, In: *Proceedings of the 30th Annual International Conference of IEEE EMMBS*, Vancouver, canada, pp. 5266-5269
12. De Rossi D., Bartalesi R., Lorussi F. et al. (2006). Body gesture and Posture Classification by Clothes, In: *Proceedings of the 1st IEEE / RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics.* pp. 1189 – 1193

13. Dijcker R., Van Der Wijk M. (2011). Geotextile Enabled Smart Monitoring Solutions for Safe and Effective Management of Tailing and Waste Sites. Two Case Studies: Volgermeerpolder (The Netherlands) and Suncor (Canada). In: *Proceedings Tailing and Mine Waste*, Vancouver, pp.1-8
14. Dunne L., Walsh P., Smyth B., Cauldfield B. (2006). Design and Evaluation of a Wearable Optical sensor for Monitoring Seated Spinal Posture. In: *10th IEEE International Symposium on Wearable Computers Proceedings*, pp. 65-68
15. Dunne L., Walsh P., Smyth B., Caulfield B. (2007). A System for Wearable Monitoring of Seated Posture in Computer Users. In: 4th International Workshop on Wearable and Implantable Body Sensor Networks Proceedings, 13, pp.203-207
16. Fereira da Silva A., Rocha R.P, Carmo J.P., Correi, J.H. (2013). Photonic Sensors Based on Flexible Materials with FBGs for Use on Biomedical Applications. In: *Current Developments in Optical Fiber Technology*, InTech, pp.105- 132
17. Gerhardt L.-C., Lottenbach R., Rossi R.M., Derler S. (2013). Tribological Investigation of a Functional Medical Textile with Lubricating Drug-Delivery Finishing. *Colloids and Surfaces B: Biointerfaces*, Vol. 108, pp.103-109
18. Gniotek K., Frydrysiak M., Zieba J. et al. (2011). Innovative Textile Electrodes for Muscles Stimulation. In: *IEEE International Workshop in Medical Measurements and Applications (MeMeA) Proceedings*, pp. 1-6
19. Harris M., Habeth, J. (2007). The MyHeart project: A Framework for Personal Health Care Applications. In: *Computers in Cardiology 2007*, pp.137-140
20. Hoerr M. (2012). *ALL4REST: Integrated Solutions for Imrove the Quality of Rest*. Project report, pp. 1-33
http://www.swisstexnet.ch/files/pdf/innoday09/innoday09_pdf07_hslu_aweber_fadler-stossevoort.pdf
https://www.academia.edu/212575/Smart_Clothes._Product_Semantics_of_Smart_Clothes
21. Image: Optical fibre integrated into a knitted structure. University of Boras, [online] [15.11.2013] Available at http://www.hb.se/en/Research/Research-areas/Textiles-and-fashion-Design/
22. Image: Warming Blanket for Decubitus Prophylaxis by Moeck Warming Systems, Moeck&Moeck GmbH [online] [29.11.2013] Available at : http://www.moeckundmoeck.de/wds/wd-gkd.php
23. Image: Wearable Motherboard™ [online] [27.11.2013] Available at: www.portfolio.io.utwente.nl
24. Keller T., Kuhn A. (2008). Electrodes for Transcutaneous (Surface) Electrical Stimulation. *Journal of Automatic Control*, Vol. 18, pp.35-45
25. Lauterbach C., Steinhage A., Techmer A. (2013). A Large-Area Sensor System Undernearth the Floor for Ambient Assisted Living. *Prevasive and Mobile Sensing and Computing for Healthcare*, Vol. 2, pp. 69-87
26. Lenting H. (2012). Multifunctional Medical Textiles for Wound Prevention and Improved Decubitus Wound Healing: Research Results and Experiences on the Road of Implementation. Seminar: *Medical Smart Textiles. Chances, Challenges and Medical Needs*, November 15, Insitut fuer Textiltechnik, Aachen
27. Li H., Yang H., Li E. et al. (2012). Wearable Sensors in Intellegent Clothing for Measuring Human Body Temperature Based on Fiber Bragg Grating. *Opitics Express*, 20(11), pp. .
28. Li L., Au W.M., Li Y. (2009). Design of Intelligent Garment with Transcutaneous Electrical Nerve Stimulation Function Based on the Intarsia Knitting Technique. *Textile Research Journal*, pp. 1-8
29. Lorussi F., Scillingo E.P., Tesconi M. et al. (2005). Strain Sensing Fabric for Posture and Gesture Monitoring. *IEEE Transactions on Information Technology in Biomedicine*, Vol. 9, pp.372-381
30. Moriss D., Coyle S., Wu Y. et al. (2009). Bio-Sensing Textile Based Patch with Integrated Optical Detection System for Sweat Monitoring, *Sensors and Actuators B: Chemical*, 139, pp. 231-236

31. Narbonneau F., De Jonckheere J., Jeanne M. et al. (2010). OFSETH: Optical technologies embedded in smart medical textile for continuous monitoring of respiratory motions under Magnetic Resonance Imaging. In: *Proceedings of SPIE-The International Society for Optical Engineering*, Vol.7715, pp.77151 -77163
32. Nocke A., Schroeter A., Cherif C., Gerlach G. (2012). Miniaturized Textile-based Multi-layer pH-Sensor for Wound Monitoring Applications. *Autex Research Journal*, Vol.12, No.1, pp. 20-22
33. Paradiso R., Loriga G., Taccini N. (2005). Wealthy- a Wearable Monitoring System: New Frontier on E-Textiles, *Journal of Telecommunication and Information Technology*, Vol. 4.pp. 105-111
34. Park S., Jayaraman S. (2001). Adaptive and responsive textile structures (ARTS). In: *Smart Fibers, Fabrics and Clothing*, Cambridge, Woodhead Publishing, pp.226-245
35. Pasche S., Schyrr B., Wenger B. (2013). Smart Textiles with Biosensing capabilities. *Advances in Science and Technology*, 80, pp.129-135
36. Pereira T., Silva P., Carvalho H., Carvalho M. (2011). Textile Moisture Sensor Matrix for Monitoring of Disabled and Bed-Rest Patients, *IEEE International Conference on Computure as a Tool (Eruocon)*, pp. 1-4
37. Product catalog of TherMedic: *Pro-Wrap Series (3 in 1 hot, cold, brace therap*y), [online] [18.11.2013] Available at: http://www.mythermedic.com
38. Rantanen J, Alfthan N., Impiö J. et al. (2000) Smart Clothing for the Arctic Environment. In: *Proceedings of the Fourth International Symposium on Wearable Computers (ISWC'00)*, pp. 15-23
39. Rattfält L., Björefors F., Nilsson D. et al. (2013). Properties of Screen Printed Electrocardiography Smartware Electrodes Investigated in an Electro-Chemical Cell. *Biomedical Engineering OnLine*, Vol. 12 (1), pp. 1-11 [online] [01.12.2013] Available at: http://www.biomedical-engineering-online.com/content/12/1/64
40. Rigby A.J., Anand S. (2000). Medical Textiles. In: *Handbook of Technical Textiles*, Cambridge, Woodhead Publishing, pp.407-424
41. Rothmaier M, Selm B., Spichtig S. et al. (2008). Photonic Textiles for Pulse Oximetry. *Optics Express*, Vol. 16, pp. 12973-12986
42. Rotsch C., Hanus., Schwabe D. et al. (2009). Textile Solutions for Diagnostic and Therapeutic Applications. In: *Proceedings International Conference Last Advances in High Tech Textiles and Textile-Based Materials*, 80 Years of department of Textiles, pp. 41-47
43. Rumpf S. (2008). Patient Monitoring System Based on Textile Sensor Technology, Innovations Forum Heidelberg [online] [27.20.12] Available at: http://www.heidelberger-innovationsforum.de/fileadmin/_heidelberger/downloads/Praesentationen_April08/15_Rumpf.pdf
44. Scharp D. (2013). Printed Composite Electrodes for In-Situ Wound pH Monitoring. Biosensors and Bioelectronics, pp.399-404
45. Schwarz A., van Langenhove L., Guermonprez P., Deguillemont D. (2010) A Roadmap on Smart Textiles. *Textile Progress*, Vol., 42, pp.99-180
46. Sibinski M., Jakubowska M., Sloma M. (2010). Flexible Temperature Sensors on Fibres. Vol. 10, pp. 7934-7946.
47. Steffen, D., Adler F., Weber Marin A. Smart Semantics: Product Semantics of Smart Clothes. Lucerne University of Applied Sciences and Arts, Competence Center Product and Textiles [online] [18.12.2013] Available at
48. Textilien und textile Produkte-Intelligente Textilien-Definitionen, Klassifizierung, Anwendungen und Normungsbedarf; Deutsche Fassung CEN/TR 16298:2011 (2012). (Textiles and Textile Products-Smart textiles-Definitions, Categorisation, Applications and Standartization Need; German Version CEN/TR 16298:2011), DIN Deutsches Insitut fuer Normung e. V., Berlin, pp.1-32 (In German)
49. Van den Kirboom, E. Byluppala (2011). Systex-Coordination Action for Enchancing the Breakthrough of Intelligent Textile Systems (E-Textiles and Wearable Microsystems), Systex FP7-ICT-207, University of Ghent, pp. 1-91

50. Van der Schueren L., De Clerc, K. (2013). Halochromic Textile Materials as Innovative ph-Sensors. *Advances in Science and Technology*, Vol. 80., pp. 47-52
51. Van Langenhove (2007). *Smart Textiles Medicine and healthcare. Materials, Systems and Applications*, Cambridge, Woodhead Publishing, pp.3-73, 106-122, 153-300
52. Vargas S.C.(2005). Smart Clothes - Bekleidung mit integrierten oder adaptierten elektronischen Komponenten (Smart Clothes- Clothing with Integrated or Embedded Electronic Compounds), Hamburg, Diplomica Verlag, pp.1-345
53. Vincenzini P., Ross, D. (2008). Wearable Biosensors for Monitoring Wound Healing. *Advances in Science and Technology*, Vol. 57, pp.80-87
54. Weber Marin A., Adler F., Ossevoort S. (2009). Wie ein textiles Produkt kommunizeirt-Forschungsprojekt Smartsemantics (How Textile Products Communicate- Research Project Smart Semantics). Lucerne University of Applied Sciences and Arts, Competence Center Product and Textiles, [online] [15.09.2013] Available at
55. Weber MKirstein T. (2013). The Future of Smart-Textiles Development: New Enabling Technologies, Commercialisation and Market Trends. In: Multidisciplinary Know-How for Smart-Textiles Developers, Cambridge, Woodhead Publishing.
56. Weremeczuk J., Tarapata G., Jachowicz R. (2012). Humidity Sensor Printed on Textile with Use of Ink-Jet Technology, *Proc. Eurosensors XXVI*, Vol. 47, pp.1366-1369.
57. Witt, J., Schukar, M., Krebber, K. et al. (2013) Personal protective equipment with integrated POF sensors. In: *5th European Workshop on Optical Fibre Sensors Proceedings*, Vol.8794, pp. 87941-8797
58. Xie L., Yang G., Xu L. et al. (2013). Characterization of Dry Biotential Electrodes. In: *35th Annual International Conference of the IEEE EMBS*, Osaka, Japan, July, 2013, pp. 1478- 1482
59. Zysset C., Nasseri N., Buether L. et al. (2013). Textile integrated Sensors and Actuators for Near-infrared Spectroscopy. *Optics Express*, Vol. 21 (3), pp. 1-12