2007

Smart nanotextiles: a review of materials and applications

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Keywords
Smart, nanotextiles, review, materials, applications

Disciplines
Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details
Coyle, S., Wu, Y., Lau, K., De Rossi, D., Wallace, G. G. & Diamond, D. (2007). Smart nanotextiles: a review of materials and applications. MRS Bulletin, 32 (May), 434-442.

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Smart Nanotextiles: A Review of Materials and Applications

Shirley Coyle, Yanzhe Wu, King-Tong Lau, Danilo De Rossi, Gordon Wallace, and Dermot Diamond

Abstract

The development of smart nanotextiles has the potential to revolutionize the functionality of our clothing and the fabrics in our surroundings. Nanoscale manipulation results in new functionalities for intelligent textiles, including self-cleaning, sensing, actuating, and communicating. This is made possible by such developments as new materials, fibers, and finishings; inherently conducting polymers; carbon nanotubes; and antimicrobial nanocoatings. These additional functionalities have numerous applications, encompassing healthcare, sports, military applications, and fashion. The wearer and the surrounding environment may be monitored in an innocuous manner, giving continuous updates of individual health status or environmental hazards. More generally, smart textiles become a critical part of the emerging area of body sensor networks incorporating sensing, actuation, control, and wireless data transmission. This article reviews current research in nanotechnology application to textiles, from fiber manipulation and development to end uses of smart nanotextiles.

Introduction

Technology is becoming increasingly prominent in our daily lives, in many ways alleviating and in other ways fueling the demands of modern living. Huge opportunities exist in the textile market to extend the functionality and performance of textiles to meet these demands. The advent of smart nanotextiles will revolutionize the clothes we wear, the furnishings in our homes, and the materials used in industry. This coming revolution has heightened the expectations of textile performance, and there is a great demand for "smart fabrics" that are more perceptive of the surrounding environment. Technical and functional textiles may be enlisted in a wealth of applications ranging from military and security to personalized healthcare, hygiene, and entertainment.

Advancing the current functionalities of textiles while maintaining the look and feel of the fabric is where nanotechnology is having a huge impact on the textile industry. The market for textiles using nanotechnologies is predicted to reach $13.6 billion in 2007 and climb dramatically to $115 billion by 2012.[1]

Textiles, being a pervasive and universal interface, are an ideal substrate for integrating sensors to monitor the wearer and the environment. Textiles offer a versatile framework for incorporating sensing, monitoring, and information processing devices. Smart textiles can sense and react to environmental conditions or stimuli, for example, from mechanical, thermal, chemical, electrical, or magnetic sources.[2] Some are termed "passive smart textiles," capable of sensing environmental conditions, whereas "active smart textiles" contain both actuators and sensors, such as thermoregulating garments that maintain the wearer's body temperature.

Therefore, the fundamental components within smart textiles are sensors, actuators, and control units. The sensing elements, data transmission, and processing must be integrated into the textile while retaining the usual tactile, flexible, and comfort properties of clothing in order for the smart textile to be practical. Much work in the field of smart clothing features conventional electronics overlaid onto a textile substrate, and the problems of connections, bulkiness, wearability, and washability are well documented.[3,4]

A means of seamless integration is required to develop true textile sensors. This is why nanotechnology is key to the smart textiles industry, enabling the incorporation of new functionalities at various production stages—at the fiber-spinning level, during yarn/fabric formation, or at the finishing stage. This article describes current materials developments for smart nanotextiles and some of the many applications where these innovative textiles are of great benefit.

Materials Research

The earliest textile developments involved the use of natural materials such as cotton, wool, and flax. More recently, synthetic fibers were developed: Lycra®, a segmented polyurethane-urea, has exceptional elastic properties, and Kevlar®, poly-*para*-phenylene terephthalamide, has ultrahigh-strength properties and is used in bulletproof vests. Today, needs for personal mobility, healthcare, or rehabilitation require that novel functions in sensing and actuating be integrated into textiles. The fundamental challenge in system-on-textile design is that the drapability and manufacturability of textiles and clothing must remain largely unaffected. Materials suitable for the development of smart nanotextiles include inherently conducting polymers (ICPs), carbon nanotubes (CNTs), and a number of other materials in the forms of nanoparticles or nanofibers.

Inherently Conducting Polymers

Discovered in 1977, inherently conducting polymers (ICPs) conduct electricity and have the ability to sense and actuate.[5] Actuators based on ICPs can generate much higher stresses with a strain comparable to natural skeletal muscle,[6,7] and sensors based on ICPs can change their resistivity or generate an electrical signal in response to external stimuli.[8,9] ICP-based intelligent polymer systems have the ability to sense, process information, and actuate. Chart 1 depicts chemical structures of some commonly used ICPs.

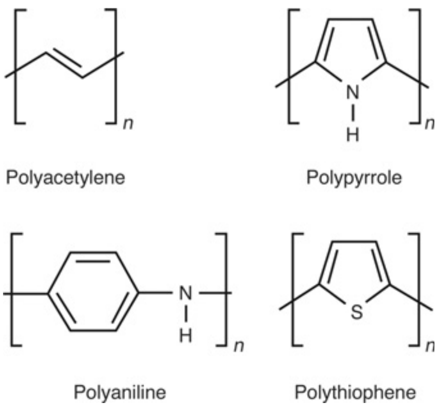


Chart 1. Chemical structures of selected inherently conducting polymers (ICPs) in the undoped form.

Most ICPs are prepared via chemical or electrochemical oxidation of the monomer in solution or in the vapor phase,[10] and incorporation of a range of dopants is possible, resulting in ICPs with varying properties. Among the available ICPs, polypyrrole (PPy) is attractive because it has high mechanical strength, is relatively stable in air, and is electroactive in both organic and aqueous solutions. Polyacetylene is unstable in air, limiting its use. Polyaniline (PANi) is one of the most widely studied ICPs, with relatively good environmental stability and good electrical conductivity. PANi has three possible configurations: leucoemeraldine base (fully reduced), emeraldine base (partly oxidized), and pernigraniline base (fully oxidized). When oxidized in aqueous protonic acids, PANi increases its conductivity by 9–10 orders of magnitude. Polythiophene and its derivatives have both *p*- and *n*-type electronic forms, which have been researched to construct polymer field-effect transistors for flexible logic circuits.[11] Moreover, extensive research has also been devoted to its use in polymer solar cells,[12] where its many advantages, such as low production costs, flexibility, and light weight, make it suitable for integration into textile fibers.[13]

The unusual electrical conduction in ICPs is achieved through a charged π-conjugated system, which is a truly nanostructured charge pathway via a long molecular chain. This pathway is stabilized by a negatively charged dopant incorporated in close vicinity; that is, all charged dopants, such as iodide, triiodide, and perchlorate, are spatially removed from the quasi-one-dimensional conduction pathway.[14,15] The resistive backscattering of electrons is reduced, and this leads to a theoretical conductivity of up to 2×10^7 S cm^{-1}, which is much higher than metal conductors.[16] However, the commonly used bulk synthesis method inevitably results in a shorter molecular chain and introduces conjugation defects, with interchain charge hopping reducing the electrical conductivity of ICPs to less than 1000 S cm^{-1}.[17]

Textiles made from ICPs may be realized by continuous wet spinning to produce ICP-based textile fibers, which can be manufactured into yarns and a range of fabric structures.[18] The conductivity changes in response to external deformation are exploited in the production of textile-based mechanical sensors such as the flexible strain gauge.[19] Particularly, PPy coated on nylon and Lycra by an *in situ* chemical polymerization process has been applied to biofeedback devices for sports training and rehabilitation.[20,21]

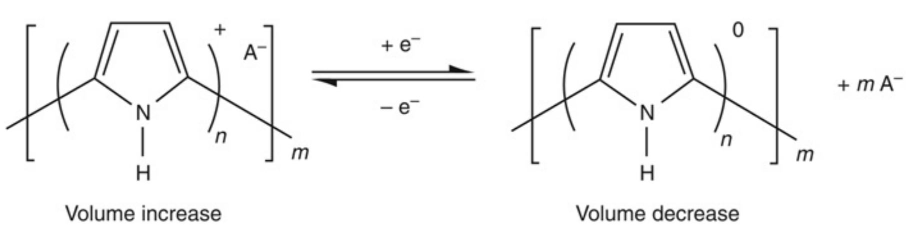
The actuation property of ICPs results from the volume change of ICPs (Reaction 1). An applied positive potential leads to the removal of electrons from the polymer backbone and the incorporation of dopant ions (A^-) to maintain electrical neutrality. The positive charges on the polymer backbone provide coulombic repulsion forces between polymer chains. Together with the incorporation of dopants, the overall volume can be varied, and this process can be reversed in a controlled fashion to produce usable mechanical work.[6] ICP-based mechanical actuators can achieve average stresses ~10 to 20 times those generated from natural muscle,[22] realize strains (>20%) comparable to natural muscle,[23] and achieve fast freestanding beam actuation with an operational frequency of up to 40 Hz.[24] Recently, more than one million redox cycles were reported using an ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate (BMI-BF_4)/PANi fiber actuator system, with a minimal decrease in actuation strain.[25]

Films of ICP nanofibers have been used as sensors to detect chemical vapors that interact with ICPs and change their conductivity. This application exploits the benefit of high surface area resulting from the small diameter of the nanofibers. Thin films made of PANi/CSA nanofibers with diameters between 30 and 50 nm (Figure 1) have been used as a chemical sensor with superior performance to vapors of acid (HCl) and base (NH_3).[8]

Moreover, by incorporating CNTs, the electrical and mechanical properties of ICPs can also be improved. For example, a PANi–CNT composite fiber was produced recently[26] using a wet spinning technique where the ultimate tensile strength and elastic modulus of composite fiber increased by 50% to 120% with an electronic conductivity of up to ~750 S cm^{-1}. The unique properties of high strength, robustness, good conductivity, and pronounced electroactivity of CNTs in the nano domain make these composite fibers potentially useful in electronic textile applications, such as the enhanced force generation when incorporated into fabric as an actuator and the improved conduction when used as the connection wire. Figure 2 shows the morphology of a PANi– SWNT (single-wall nanotube) composite fiber.

Nanoparticles: Composite Fibers and Finishings

Nanostructured composite fibers are one area where nanotechnology is already having a huge impact within the textile industry. Composite fibers employ nano-sized components such as nanoparticles, graphite nanofibers, and CNTs to improve physical properties such as conductivity and antistatic behavior. Table I lists some of the nano-sized species that are used to improve the performance of textiles.[27] These nanoparticles may be used to develop composite fibers as nanoscale fillers or through a foam-forming process and may also be applied as finishings to



Reaction 1. Incorporation and exclusion of the dopant ions in electrochemical actuation of inherently conducting polymers (ICPs), for which polypyrrole (PPy) doped with a mobile anion is shown as an example. The incorporation of dopant ions results in an increase in the total volume of polymer, while the exclusion of dopant ions results in a volume decrease. A^- represents anions incorporated into the PPy during synthesis, *n* is the number of pyrrole units for each A^- incorporated, and $n \times m$ is the number of PPy repeat units that determines the molecular weight of the polymer.

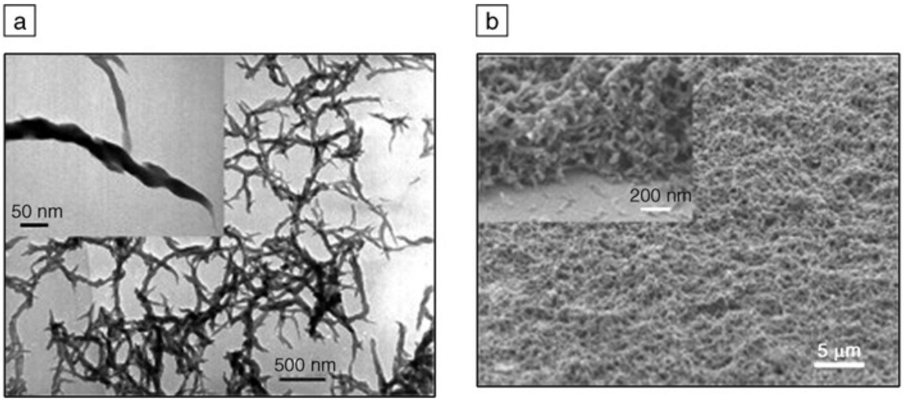


Figure 1. (a) Transmission electron microscopy images of polyaniline/camphor sulfonic acid (PANi/CSA) nanofibers cast from suspension after dialysis. Inset shows a twisted fiber. (b) Scanning electron microscopy (SEM) secondary electron images of a thin film of PANi/CSA deposited on glass from suspension. Inset shows a cross-sectional view of the film on the glass substrate.[8]

the textile, for example, spray-coating TiO_2 for biological protective materials.

Applications
Sports

The sports industry has driven much research within the textile industry to help improve athletic performance, personal comfort, and protection from the elements. Synthetics that were once thought to be inferior to natural fabrics now boast high-performance characteristics. Numerous products designed to improve the comfort of the wearer are commercially available; for instance, there are breathable waterproof fabrics such as Gore-Tex® and moisture-management textiles that wick moisture away from the skin such as Coolmax®. Gore-Tex® fabric uses a membrane of expanded poly(tetrafluoroethylene) (PTFE) that has pores of less than 1 μm in diameter, allowing water vapor to penetrate the material, but preventing the passage of liquid. To maintain the wearer's comfort, it is important that sweat is allowed to evaporate, maintaining the body's natural thermoregulatory function. High-performance moisture-wicking fabrics worn next to the skin transport perspiration away from the body to the outside of the garment where it can more quickly evaporate. This is achieved using synthetic microfibers that, unlike natural fibers, do not absorb moisture, but rather pass it through by a wicking effect that makes them more comfortable to wear. It is even possible to maintain constant body temperature using phase-change technology such as Outlast Adaptive Comfort®. Phase-changing materials (PCMs) absorb, store, and release heat as the material changes phase from solid to liquid and back to solid. A microencapsulation process is used to capture small amounts of phase-change material in a polymer shell so that it is permanently enclosed and protected. These microencapsulated PCMs, developed by Outlast Technologies Inc. and called Thermocules®, can then be applied as a finishing on fabrics or infused into fibers during the manufacturing process.

Through the use of nanotextiles, clothes are adapting to their wearers, meeting their needs, and maintaining their comfort. The adidas_1 running shoe uses sensors, a microprocessor, and a motor to adjust its shock-absorbing characteristics to the individual runner's style, pace, body weight, and running surface.[28] Nike has also released a smart running shoe containing a wireless sensor that connects to an iPod with various playlists to match the type of workout while also tracking distance, time, pace, and calories burned.[29] Textiles are engineered to improve performance; for example, nanotech swimsuits for Olympic swimmers have been developed to reduce drag

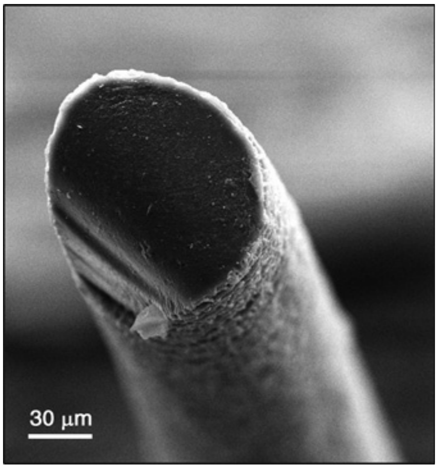


Figure 2. Cross-sectional SEM image of polyaniline–single-walled nanotube composite fiber.

Table I: Properties and Applications of Nanoscale Materials Used to Improve Textile Performance.

Nano-Filler	Properties/Applications
Carbon nanofibers	Increased tensile strength High chemical resistance Electrical conductivity
Carbon black nanoparticles	Improved abrasion resistance and toughness High chemical resistance Electrical conductivity
Clay nanoparticles	Electrical, heat, and chemical resistance Block UV light Flame retardant, anticorrosive
Metal oxide nanoparticles (TiO_2, Al_2O_3, ZnO, MgO)	Photocatalytic ability Electrical conductivity UV absorption Photo-oxidizing capacity against chemical and biological species Antimicrobial/self-sterilization
Carbon nanotubes	100× tensile strength of steel at one-sixth the weight Electrical conductivity similar to copper Good thermal conductivity

by using a biometric knitted construction of nylon/elastane with v-shaped ridges that emulate a shark's skin.[30] The latest developments integrate sensing capabilities to provide instantaneous awareness of the physiological condition of the athlete, thus providing valuable information about the athlete's physical abilities, training status, athletic potential, and responses to various training regimens. There is a great demand for wearable sensors to be used in the field for kinematic analysis, monitoring of vital signs, and biochemical analysis.[31]

Strain sensors made from piezoelectric materials may be used in biomechanical analysis to provide wearable kinesthetic interfaces able to detect posture, improve movement performance, and reduce injuries.[32] The conductivity of these textiles is affected by stress and strain applied to the fabric, which can be used to assess physiological movements that impose strain or pressure on the material. Garments integrating piezoresistive ICPs and conductor-loaded rubbers with strain-sensing capabilities offer continuous monitoring of body kinematics and vital signs.[21,33–35] The advantage of this approach is that the tactile and flexible properties of the textile are maintained, providing truly wearable fabrics.

Such devices may be used to teach athletes the correct way to perform movement skills by providing real-time feedback about limb orientation. Examples of such devices are shown in Figure 3. Figure 3a shows a carbon-loaded elastomer-sensorized garment developed at the University of Pisa. The piezoresistive sensors are fabricated on a Lycra®/cotton textile by masked smearing of the conducting mixture, which consists of a silicone matrix filled with carbon black powder. The same polymer/conductor composite is also used as material for the connection tracks between sensors and an acquisition electronic unit, avoiding the stiffness of conventional metal wires. Figure 3b shows the Intelligent Knee Sleeve, developed through a collaboration between the Intelligent Polymer Research Institute and Biomedical Science at the University of Wollongong and CSIRO Textile and Fiber Technology. It is a biofeedback device using PPy sensors that monitors the wearer's knee joint motion during jumping and landing to reinforce the correct landing technique.[34] The PPy-coated fabric acts as a strain gauge, with a wide dynamic range, and is connected to a microcontroller that emits an audio tone when the knee bends beyond a pre-set angle. The device was developed for sports where jumping-related knee injuries are common and may also be used as a rehabilitation device following injury.

In addition to their application as strain gauges, conducting polymers have been demonstrated to function as pressure

Figure 3. (a) Carbon-loaded elastomer-sensorized garment for kinesthetic monitoring developed at the University of Pisa. (b) The Intelligent Knee Sleeve is a biofeedback device using PPy sensors that monitors the wearer's knee joint motion. (Courtesy of CSIRO Textile and Fiber Technology.)

sensors by combining them with compressible textiles. Polyurethane (PU) foam coated with PPy sensors was developed at Dublin City University. The sensor remains soft, compressible, versatile, and, in contrast to conventional coated textiles, is sensitive to forces from all three dimensions. The PPy-coated PU foam has been used for developing a breathing monitor, whereby the foam sample is incorporated into a harness to wrap around the ribcage area. The movement of the ribcage during breathing exerts pressure on the conducting foam, causing an increase in conductivity of the material. It has also been integrated into the armhole of a shirt to detect joint movements of the upper limbs, and smart insoles monitoring plantar pressure have been demonstrated for gait analysis applications.[36,37]

A new area of research that will have a major impact for sports performance involves integrating chemical sensors into textiles. The aim of the European Union (EU)–supported BIOTEX (bio-sensing textile for health management) project[38] is to perform real-time analysis of the various constituents in sweat. Research in this area is unfortunately lacking, because of the overwhelming focus on blood-based diagnostics. The approach being taken is to integrate electrochemical and optical sensors within a textile substrate, enabling the direct collection of sweat from a large body surface area. The target analytes include sodium, chloride, pH, sweat rate, and sweat conductivity in addition to monitoring cardiac and respiratory functions.[38] This is of particular interest in sports applications where rehydration strategy plays a critical role in the recovery process after exercise. It is important not only to replace volume losses due to sweat, but also electrolytes. These factors are highly variable among individuals, and current techniques are impractical, involving sweat patches that must be sent to a laboratory for analysis. BIOTEX is developing a wearable system incorporating a fluid handling platform based on moisture-wicking fabrics and nonwoven superabsorbent textiles. The sensing elements are integrated within the fabric's fluidic channels to monitor the sweat composition. Control electronics and wireless data transmission allow real-time analysis of the signal and give feedback to the wearers regarding their well-being, making individuals more aware of their personal healthcare needs.

Healthcare

The interest in smart textiles for healthcare arises from the need to monitor patients for extensive periods because of rehabilitation or chronic illness. The problem with conventional clinical visits in these cases is that they can only provide a brief window on the physiology of the patient;[39] wearable devices offer the possibility to monitor physiological signals continuously in a realistic setting. This is vital for the future of the healthcare system, given the global aging population. There is a need to shift the focus of healthcare expenditures from treatment to prevention and wellness promotion.[40]

The EU has funded a number of interrelated, specifically targeted research projects in this area. The WEALTHY (Wearable Health Care System) and MyHeart projects involve wearable textile interfaces integrating sensors, electrodes, and connections realized with conductive and piezoresistive yarns[41,42] to tackle cardiovascular diseases, which are the leading cause of death in the Western world. The WEALTHY system is made up of a sensorized cotton/Lycra® shirt that integrates carbon-loaded elastomer strain sensors and fabric bioelectrodes, enabling the monitoring of respiration, electrocardiogram (ECG), electromyogram (EMG), body posture, and movement. Electrodes, to detect ECG and EMG signals, are knitted using stainless steel–based yarns, and a hydrogel membrane is applied to improve contact and match impedance with the skin. New products coming onto the market for similar applications include the SmartShirt by Sensatex™ and the Life Shirt® system by VivoMetrics®, offering continuous ambulatory monitoring systems.

There is also potential for monitoring emotional, sensory, and cognitive activities, as demonstrated by the MARSIAN system (Modular Autonomous Recorder System for the measurement of Autonomic Nervous system). The system includes a smart glove with sensors for the detection of the activity of the autonomic nervous system, which is responsible for the body's involuntary vital functions. The glove contains noninvasive sensors to measure physiological parameters such as skin temperature, skin electrical conductance, and skin potential. A microsensor (0.45 mm) is integrated into the glove to monitor skin temperature, and electrodes measure the skin's electrical activity. The initial approach to electrode integration was to embroider commercially available silver/silver chloride electrodes into a hairnet glove, while a recent prototype uses a 3D structure made of Kapton® copper foil (150 µm thick) with electrodes covered in silver.[43]

One of the more recent endeavors within the EU roadmap is the ProeTEX project (advanced e-textiles for firefighters and civilian victims) to perform on-body biochemical sensing within a textile. While BIOTEX fabrics, as discussed previously, monitor the wearer's health,[44] ProeTEX fabrics monitor the surrounding environment to detect any potential risks. The project plans to develop a full system for firefighters and civil protection workers plus a limited system for injured civilians. The wearable sensing and transmission systems will be able to monitor health, activity, position, and environment, with information relayed both to the individual and also to a central monitoring unit.

ICPs used for kinesthetic and physiological monitoring, as discussed previously for assessing sports performance, may also be used in the area of patient rehabilitation.[45] These electroactive polymers, typically PANi and PPy, are used as sensing devices and may also be configured as actuators. For this purpose, they are used as electrodes properly configured within an electrochemical cell. By applying a potential, the ICP electrode changes its dimension and works as a mechanical actuator. Integration of such actuators within textiles would enable fabrics to have motor functions, opening a new field of applications, particularly in the development of artificial muscles. For example, ICP actuators have been developed to assist the insertion of cochlear implant electrodes, in which a prototype actuator made of a bilayer PPy actuator is able to steer or bend the electrode in a controllable manner.[46] Although the current actuation force and mechanical energy density of electroactive polymers are relatively low, there is potential to develop rehabilitative aids and orthotic limbs.[46,47]

Textiles have acted as a second skin for protection and appearance, whereas smart textiles have the potential to emulate and augment the sensory system of the skin by sensing external stimuli such as proximity, touch, pressure, temperature, and chemical/biological substances. Lumelsky et al. describe a large-area, flexible array of skin-like sensors with data processing capabilities that can be used to cover the entire surface of a machine, such as a robotic system or even part of a human body.[48] For conditions such as diabetes mellitus, where the patient loses sensation in the limbs, or for bedridden patients, pressure-sensitive fabrics may aid in assessment and warning to reduce the occurrence of pressure ulcers. PPy foam pressure sensors have been demonstrated for this purpose.[9] With nanotechnologies, smart textiles may provide a haptic interface, that is, a touch-sensitive alternative to skin.

Novel functionalities in textiles are of course not limited to personal apparel.

Home furnishings may be enlisted into ubiquitous sensing within smart homes for telemonitoring elderly, convalescent, or isolated individuals.[49,50] This aligns with the "continuity of care" concept that wearable technologies bring through monitoring patients at home in comfortable surroundings.

Military/Security

There is a need for real-time information technology to increase the protection and survivability of people working in extreme environmental conditions and hazardous situations. Performance improvements and additional capabilities would be of immense benefit to defense forces and emergency response personnel. The SmartShirt by Sensatex™ was initially developed by the Georgia Tech Research Corporation and for military applications. The T-shirt functions like a computer by means of optical and conductive fibers integrated into the garment. The optical fibers are used to detect bullet wounds, pinpointing their exact location, and various sensors are used to monitor the body's vital signs during combat conditions.[51]

The Institute for Soldier Nanotechnologies (ISN) is an interdepartmental research center at the Massachusetts Institute of Technology. The ISN's research mission is to use nanotechnology to dramatically improve soldier survival. The intention is to secure a lighter, faster, more agile force with a heightened awareness of its environment and potential threats. Wireless networking enables medics to monitor the health status of the soldier. The ultimate vision of the battlesuit of the future is a bulletproof jumpsuit, no thicker than ordinary spandex, that monitors health, eases injuries, transmits data automatically, and enables medics to conduct remote triage of combat casualties to help them respond more rapidly and safely.[52]

The chemical-sensing properties of conductive polymers coated onto woven fabric materials were investigated to detect hazards that may endanger the health of the wearer. Low-ppm detection limits were demonstrated for toxic gases such as ammonia and nitrogen dioxide as well as the chemical warfare simulant dimethyl methylphosphonate (DMMP).[53] Fiber-optic sensors with modified cladding materials are suitable for detecting hazards on the battlefield and may be easily integrated into soldiers' uniforms. The original cladding material is replaced with a chemical agent or environmentally sensitive material on a small section of the fiber. The modified cladding material may be sensitive to different environmental conditions, causing a change in the refractive index. This affects the propagation of the transmitted light signal, which can be measured using optical detection techniques. El-Sherif et al. demonstrated this using a thermochromic agent, segmented polyurethane-diacetylene copolymer, and a photochemical polymer, PANi, as cladding agents.[54]

Fashion/Lifestyle

The development of high-tech advanced textiles for specific applications, such as extreme sports, eventually finds its way to street fashion, where designers are allowed the creativity of experimenting with these new emerging materials. Microfibers, for example, were initially developed for space and military applications, and are now used in sportswear, interior fabrics, and fashion.[55]

We have become exceedingly reliant on technology; for instance, at any one time, the typical person may be carrying an MP3 player, a laptop computer, a mobile phone, a computational wristwatch, and a digital camera. The components of these devices are being continually miniaturized and, with methods such as thin-film technology, the electronics are becoming more flexible. Such advancements are enabling the technology to integrate more easily into our lives and onto our clothes. Eleksen has developed fabric touch pads integrated into jackets for more accessible control of MP3 players. The initial application was for snowboarding jackets to provide ease of access to the control buttons. Eleksen has also developed a fabric keyboard for personal digital assistants (PDAs) that can be rolled out, easily stored, and transported (Figure 4). Another producer of electronic textiles, Textronics, develops fabrics that can warm, illuminate, conduct, and sense. One of their recent developments is the NuMetrex heart rate monitoring sports bra, which incorporates conductive knitted sensors that link wirelessly to a heart-rate-monitoring watch.

Nanocoatings now offer advanced protection to improve hygiene and cleanliness. To add antibacterial properties, nano-sized silver, titanium dioxide, and zinc oxide[12] are used. Metallic ions and metallic compounds display a certain degree of sterilizing behavior. It is considered that part of the oxygen in the air or water is turned into active oxygen by means of catalysis with the metallic ion, thereby dissolving the organic substance to create this sterilizing effect. By using nano-sized particles, the number of particles per unit area is increased, and thus, antibacterial effects can be maximized. Antimicrobial coatings are widely applied to socks in order to prohibit the growth of bacteria, but their uses also extend from wound dressings to home furnishings,

Figure 4. Elektex fabric-based keyboard (30 × 11 cm; weight, 65 g). (Courtesy of Eleksen.)

carpets, and clothing.[56] Another innovation for such purposes is superhydrophobic self-cleaning surfaces. This was first inspired by the natural cleanness of plant leaves such as the lotus leaf. Water coming in contact with a superhydrophobic surface (contact angle, >150°) forms nearly spherical droplets. Contaminants, either inorganic or organic, adhere to the water droplets and are removed from the surface when the water rolls off. Nano-Tex has a range of products using such coatings to resist spills, repel and release stains, and resist static.[57] These textile enhancements become inherent to the fabric, improving the performance and durability of everyday apparel and interior furnishings.

Although technology may be hidden through invisible coatings and advanced fibers, it can also be used to dramatically change the appearance of the textile, giving new and dazzling effects. Luminex® is a fabric with fiber-optic strands woven into it, which are then illuminated using light-emitting diodes (LEDs). Luminex® has been incorporated into glowing clothes, safety garments, handbags, furniture, and even a wedding dress. Another recent development is the Lumalive fabric from Philips, featuring flexible arrays of colored LEDs fully integrated within the fabric (Figure 5). These light-emitting textiles can carry dynamic messages, graphics, or multicolored images. Based on concepts of color and light therapy, brightness and the color appearance of light[58] are thought to affect mood; these textiles are designed to enhance the observer's mood and positively influence his or her behavior.[59]

Figure 5. Lumalive textile garment from Philips features flexible arrays of colored light-emitting diodes fully integrated into the fabric. (Courtesy of Philips.)

Conclusions

Developments in smart nanotextiles may affect many aspects of our daily lives and produce clothing that is contextually aware. New materials integrating novel technologies enable passive, noninvasive sensing of wearers and their environs. A major problem in wearable computing at present is the interconnections, with conventional silicon and metal components being highly incompatible with the soft textile substrate. By integrating technology at the nanoscale, the tactile and mechanical properties of the textile may be preserved, retaining the necessary wearable and flexible characteristics that we expect from our clothing. Smart textiles must be flexible enough to be worn for long periods of time without causing any discomfort in order to become a viable and practical product.

Smart textiles have a large range of applications, often starting as a highly specialized application before becoming a more generally available consumer product. The topics covered here show that this is an area of interdisciplinary research that must involve materials research, sensor technologies, engineering, wireless networking, and computer applications. Creating a wearable garment integrates textile and fashion design with input from the end users, such as healthcare workers, defense forces, and sports physicians. Market trends suggest great opportunities for nanotechnology within the textile market; given the current pace of development, smart nanotextiles will form a ubiquitous part of our lifestyle. Our clothing is becoming contextually aware and is learning to adjust to suit the individual needs of the user.

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