Testing and evaluation of wearable electronic textiles and assessment thereof

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4.1 Introduction

During the last decade, textiles entered a new era of *smart textiles*. Mainly, smart textiles are defined as textiles that interact with their surroundings. They can be described as textile materials that think for themselves, for example through the incorporation of electronic devices or smart materials (Stoppa and Chiolerio, 2014).

According to functional activity (Sinclair, 2014; Van Langenhove and Hertleer, 2004), smart textiles can be classified in three different categories:

- I generation → able to sense the environment/user, based on sensors (Passive Smart Textiles);
- II generation → reactive, sensing stimuli from the environment, integrating an actuator function and a sensing device (Active Smart Textiles). The actuators act upon the detected signal either directly or from a central control unit;
- III generation →able to sense, react, and adapt their behavior to the given circumstances (Ultra Smart Textiles, UST).

Electronic textiles, known as *e-textiles*, are a subset of smart textiles. They refer to a textile structure with electrical functioning similar to electronics, but physically behaving as a textile at the same time. In general, the development of electronic textiles supports the idea of wearable computing, or electronic devices into garment designs (Van Langenhove, 2007). Generally, e-textiles comprise the following components:

- sensors to detect body/environmental parameters;
- a data processing unit to collect and process the obtained data;
- an actuator that can give a signal to the wearer;
- an energy supply;
- interconnections for both power and signal;
- a communication device that establishes a wireless communication link with a nearby base station.

A variety of physiological and behavioral measurements relevant to clinical rehabilitation have been enabled through the integration of sensors within a fabric substrate (Fleury et al., 2015). For instance, fabric sensors can be used for electrocardiogram (ECG) (Alzaidi et al., 2012), electromyography (EMG) (Benatti et al., 2014), and electroencephalography (EEG) (Löfhede et al., 2012) sensing. In these applications,

Performance Testing of Textiles. http://dx.doi.org/10.1016/B978-0-08-100570-5.00005-0
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signal quality has generally been the primary consideration while user comfort and sensor integration have become secondary.

Moving beyond the biosignal sensing, several types of sensors based on textiles can be used for others purposes, such as: temperature sensing (Laukhina et al., 2014), hosting conductive fibers into fabric that responds with a temperature variation; biophotonic sensing (Omenetto et al., 2011) using luminescent elements integrated with normal fabric; sensing movements (Grillet et al., 2008) or strain events using shape-sensitive fabrics; gas detection (Windmiller and Wang, 2013) adopting fibers able to change their electrical properties when a particular chemical agent is presented near the sensor.

Active functionalities could include energy storage (Vatansever et al., 2011), human interface elements (Schneegass et al., 2014), radio frequency (RF) functionality, or assistive technology (Black, 2007). This category also comprises smart textiles with a power generation feature and it can be achieved through piezoelectric elements (Nilsson et al., 2014) that harvest energy from motion, or photovoltaic elements (Lee et al., 2013).

UST are the new ultimate frontier of the innovation in this field. Reached through a successful fusion between textile technology and material science, mechanics, biology, sensor and actuator technology, etc., this innovation is currently ongoing. An example for all could be textiles with embedded stimuli–response polymers, able to change their properties thanks to environmental stimuli, and in the meantime could produce an action, such as drug release. Coupling these smart textiles with electronics and/or computational architectures would lead to fully integrated and autonomous systems (Hu et al., 2012b).

This intelligent yarn will form the basic building blocks of truly flexible, drapeable, and washable textile computers in the near future, creating third-generation wearable computing.

This chapter provides a review of e-textiles, describing the state of the art about research and development of wearable systems reporting the salient characteristics, the manufacturing methods, and the relative functional property characterization and assessment from different levels of integration. Each scientific approach will be followed by some related work carried out by companies, universities, or research institutes.

4.2 e-Textiles manufacturing methodologies and characterization

Fabrics present a hierarchical structure based on fibrous materials. This particular architecture allows the development of e-textiles from different levels of integration and in recent years; several companies and researchers worked to seek the most efficient manufacturing process.

In order to understand the different levels, Fig. 4.1 presents the hierarchical structure of the fabric and the most common processing techniques.

Fibers are the first integration level. They are characterized by having a high length-to-thickness ratio (Needles, 1981). Yarns are the second level of integration,

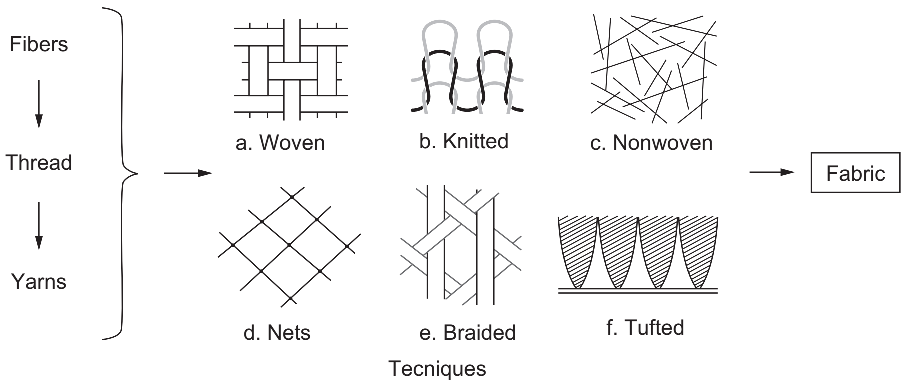


Fig. 4.1 Fabric construction platforms and relative techniques.

and through different manufacturing processes, yarns get turned into fabric, reaching the third level of integration. By coupling different layers of fabric, other levels can be developed (ie, 3D textiles) (Ansar et al., 2011).

Starting from these levels, different e-textile manufacturing methods have been invented and developed. In parallel, different base materials have been tested to achieve the best electrical behavior, near the traditional electronics features, according to the final applications.

4.2.1 Conductive fibers

Conductive fibers are a mix of electric wires and the textiles world, with attributes of each. These fibers consist of a nonconductive or less-conductive substrate, which is then either coated or embedded with electrically conductive elements (Kallmayer and Simon, 2012). Straddling the worlds of textiles and wires, conductive fibers are sold either by weight or length, and their geometry/density is measured in denier and AWG (Winterhalter et al., 2005).

Initially, conductive fibers were mainly used in technical areas such as: clean room garments, military apparel, medical application, and electronics manufacturing (Resistat, 2015). They can have a variety of functions, like antistatic applications (Sophitex, 2015), ElectroMagnetic Interference shielding (LessEMF, 2015), electronic applications, infrared absorption or protective clothing in explosive areas (Mcfarland et al., 1999).

In order to use these conductive fibers in the preceding applications, it is important that they should be strong, flexible, environmentally stable, and resistant to chemical agents.

Especially for clothing, tactile properties such as stretch, shear, and handle are quite relevant. The tactile comfort is related to mechanical interaction between the clothing material and the human body and is an intrinsic and essential performance requirement in clothing. Fabric handle is concerned with the feeling of the material and so depends upon the sense of touch for a subjective evaluation of an expert (Sülar and Okur, 2008).

For this reason the fibers should be fine and fabrics should have a low weight per unit area (not more than 300 g/m^2) (Statex, 2015). These demands are inconsistent with the materials and geometries that are needed for electrical conductivity purposes. Fig. 4.2 shows different types of conductive (black) and insulating (white) structures of conductive fibers. Each of those could have different applications, for example a shell conductive fiber is best applied where there is no need for bulk signal transmission (low frequency and high power, while rising the frequency for the so-called skin effect the conduction is sustained in the very superficial layer of a conductor), a wholly conductive fiber is not supposed to suffer from surface modification/oxidation, a core conductive fiber is normally the solution for avoiding surface modification/oxidation, and so on.

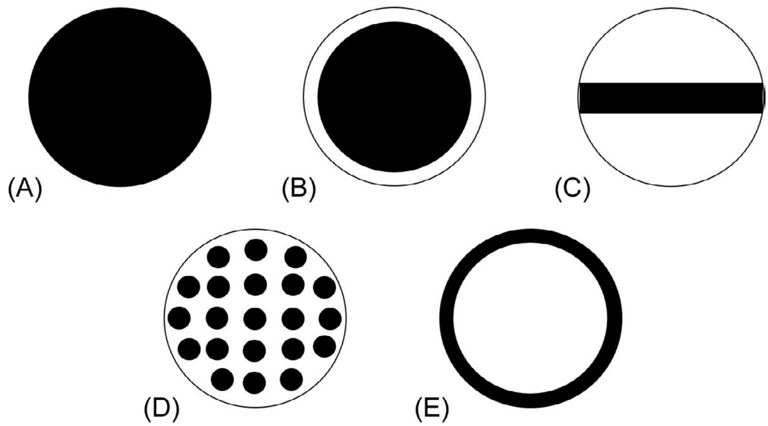


Fig. 4.2 (A) Wholly conductive fiber; (B) core conductive fiber; (C) sandwich-type fiber; (D) coated yarns, and (E) shell conductive fiber.

Different methods of conductive fiber manufacturing are available today, such as melt spinning, wet spinning (Pereira et al., 2000), electrochemical processing (Araki et al., 2011), or coating (Yamashita et al., 2012) of conventional insulating materials with conductive materials.

Following the manufacturing processes adopted, the conductive fibers can be divided into *intrinsic* or *extrinsic* (Bashir, 2013). These processes show different advantages and disadvantages as summarized in Table 4.1. The *intrinsic* conductive fibers are made by materials featuring high electrical conductivity, and in particular:

- *metallic* and *metallic alloy fibers* are very thin metal filaments with diameters ranging from 1 to 80 μm and they are made by the bundle-drawing or shaving process (Meoli and May-Plumlee, 2002). Metal content for clothing is difficult to process and also reduces the comfort of the final product. Their inertness degree, in other words, their likeliness to be sensitive to washing or sweating, depends on the metal used to create the filament. They cannot provide uniform heating and their brittle characteristics can damage spinning machinery over time (Araki et al., 2012);
- *carbon fibers* have a graphite-like structure with a conductivity comparable to that of metal (10^4–10^6 S/cm) (Dalmas et al., 2006);

Table 4.1 Advantages and disadvantages using intrinsic and extrinsic process with different base materials

Process manufacturing	Material	Advantages	Disadvantages
Intrinsic	Metallic and metallic alloy fiber	High conductivity (10^6 S/cm) and mechanical resistance[a]	Low flexibility, stiffness, high weight, and poor weaving properties[b]
	Carbon fibers	High conductivity, strength, stiffness, low weight, and high fatigue resistance[c]	Hard integration into knitted and weaved structure and harmful to health[c]
	Instrinsically conducting polymers (ICPs)	Medium conductivity (~200 S/cm) and low weight[d]	Poor mechanical strength, brittleness, and difficult processing[e]
Extrinsic	Conductive filled fibers	High conductivity[f]	High manufacturing cost[g]
	Conductive coated fibers	High conductivity (10^6 S/cm) and mechanical properties[h]	High manufacturing cost, stiffness, brittleness, and high weight[i]

References:
[a]Tibtech (2015).
[b]Meoli and May-Plumlee (2002).
[c]Hunt et al. (2012).
[d]Baik et al. (2009).
[e]Pomfret et al. (2000).
[f]Bigg Battelle (1977).
[g]Shirakawa et al. (1977).
[h]Xue et al. (2004).
[i]Sen (2007).

- *Intrinsically conducting polymers* (*ICPs*) are organic conductive materials based on polyaniline (PANI), poly(3,4-ethylenedioxithiophene)polystyrene sulfonate (PEDOT:PSS), or polypyrrole (PPy) (Ding et al., 2010; Bocchini et al., 2013).

Taking into account the *extrinsic* conductive fibers, they are made by the combination between conductive and nonconductive materials. Special treatments involve the mixing, blending, or coating process. These approaches guarantee good electrical and mechanical properties of the treated materials. These fibers can be divided into:

- *conductive filled fibers*, which are made by adding conductive fillers (eg, metallic powder, metallic nanowires, carbon nanotubes (CNTs) or ICPs) into nonconductive polymers such as polypropylene, polystyrene, or polyethylene (Thongruang et al., 2002). Melt spinning and solution spinning are the common processes to develop this kind of fiber. The solution spinning process guarantees fibers with improved electrical and mechanical properties over those produced by the melt spinning;

- *conductive coated fibers* are produced by coating insulating materials with conductive ones (eg, carbon black, metals, CNTs or ICPs) (Xue et al., 2004). The properties of these fibers depend on the type of conductive materials used and the relative manufacturing method. Metallic coatings, sputtering, vacuum deposition, and filling or loading fibers are the most common methods applied. Adopting carbon black, CNTs and ICPs as a thin layer to a fiber surface through solution casting, inkjet printing, chemical vapor deposition or vapor phase polymerization methods (Im and Gleason, 2007) improve the quality of the conductive fibers.

Electrical and mechanical properties are correlated to each other and the resistance variation of spun conductive fibers, depending on tensions applied. Flexibility is defined as the resistance to permanent deformation under stresses, such as folding or bending. It can be improved through textile processes such as spinning or twisting because the overall geometry of the yarn is a prior factor to those of individual fibers. Generally, the ASTM D1388 (or Federal Test Method Standard 191A-5200 for USA) hanging loop test has been the most well-known test method to evaluate bending behavior of the fabrics (Materials, 2012). A typical machine is the Taber Fabric Stiffness Tester that provides a quick and accurate test method for flexural rigidity employing the principle of cantilever bending (Taber Industries, 2015). This method has been properly adapted for textiles that host metal fibers and metalized polyester shielding, due to the fact that the materials increase their stiffness in comparison to any conventional textile. The reference parameter, bus stiffness (K_b (N/in.)), is calculated as the ratio between the force (F) applied and the relative displacement Δl obtained (see Eq. 5.1).

$$K_b = \frac{F}{\Delta l} \tag{5.1}$$

Another parameter to evaluate the bending properties is the sewability of multiple conductive fibers. The method adopted for this evaluation is the curl test described previously (no International Standard available); it is able to check the residual curling of a conductive wire compared to a conventional sewing thread (Orth, 2002). As mentioned previously, adding conductive properties with a metal part, the mechanical properties are affected and the curl test allows us to understand if a conductive wire is eligible for machine sewing or not.

Washability is another relevant feature to consider and it is related to chemical resistance against moisture and detergents as well as physical resistance against mechanical stresses and high temperature. Generally, washing tests are conducted in order to accelerate aging for conventional electronics (Zeagler et al., 2013). The test comprises the use of a standard upright agitator machine (eg, GE Spacemaker Model) and a standard detergent, in order to simulate an ordinary washing. Currently, many conductive fibers have been tested with this method and the results showed that the electrical resistance may increase by three orders of magnitude after the wash test (eg, from 3 kΩ to 3 MΩ for 30 cm of conductive strip made with Shieldex fibers size 40 22/7 PET).

Nowadays, several companies produce conductive fibers adopting different manufacturing methods. Textiles can be simply intertwined with filaments of stainless steel or other metals, or they can be covered with metals such as aluminum (Al) and magnesium (Mg). Often in literature, no distinction is made between metal wires and metal fibers. However, the Sprint Metal Company (Sprint Metal, 2015) discerns metal fibers and wires according to their diameter. While a fine wire has a diameter between 30 μm and 1.4 mm, a metal fiber possesses a diameter of 2–40 μm (Ugitech, 2015).

CanShielding company develops lightweight aprons based on carbon (Fujimori et al., 2011) and silver fibers (Dordevic, 1992), to protect X-ray technicians with improved comfort and wearability (Canshielding, 2015). This kind of fiber allows production of fabric that partially absorbs radar signals.

Swiss company Elektrisola Feindraht AG (Elektrisola, 2015) fabricates metal monofilaments that can be blended with all sorts of fibers or that can be directly used in weaving and knitting. Importantly, the material has different electrical properties (see Stoppa and Chiolerio, 2014). The products range from copper (Cu) and silver-plated copper (Cu/Ag) filaments, to brass (Ms) and silver-plated brass (Ms/Ag) filaments, to aluminum (Al) filaments, to copper-clad aluminum filaments (Elektrisola, 2015).

The company Swiss-Shield® is specialized in producing metal monofilaments which are incorporated into base yarns like cotton, polyester, polyamides, and aramides. Fig. 4.3A shows a typical conductive yarn with base-fibers and a metal monofilament twisted around them (Swiss Shield, 2015).

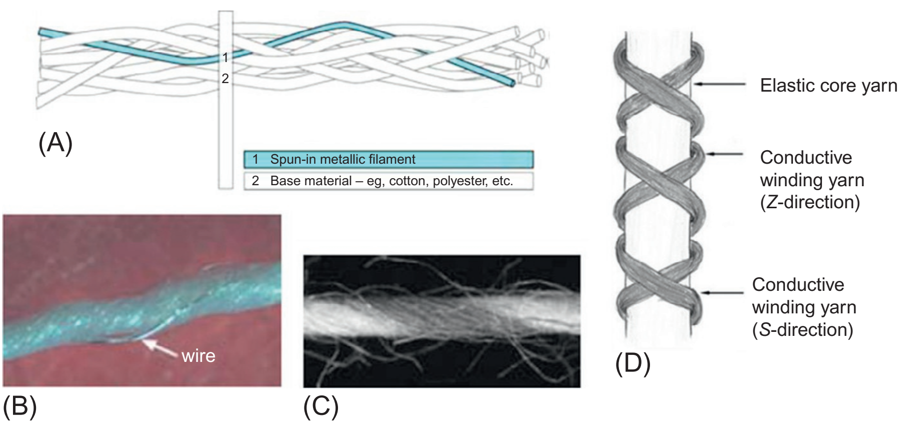


Fig. 4.3 (A) Schematic of conductive metal fiber twisted with the natural or synthetic fibers. From Swiss Shield. (B) Twisted metal wire: The metal wire is twisted around the polymer yarn. (C) Metal fibers: The conductive yarn consists of metal multifilament. (B) and (C) from Locher, I., 2006. Technologies for System-on-Textile Integration. Available at: http://e-collection.library.ethz.ch/view/eth:28457 (accessed 20.01.14). (D) Conductive winding yarns wound around an elastic core yarn in *S*- and *Z*-direction. From Schwarz, A., Kazani, I., et al., 2011. Electro-conductive and elastic hybrid yarns—the effects of stretching, cyclic straining and washing on their electro-conductive properties. Mater. Des. 32 (8), 4247–4256.

4.2.2 Conductive fabrics

After understanding the electrical properties and the manufacturing methods of the conductive fibers, to achieve a conductive fabric, the next level of integration is the conductive yarn.

Conductive yarns can be either based on nonmetallic conductive materials, such as carbon fibers, or metallic materials, as metal fibers. Such yarns can include a set of metal filaments, for example, stainless steel filaments, which can be twisted around each other. By twisting a fine metal wire around a multifilament fiber, the electrical conductivity of the yarn is achieved with an improvement of the mechanical stability (Fig. 4.3B and C).

The spiral-shape of the metal wire allows a flexibility of the whole yarn and in particular, when the yarn is stretched, the metal wire is able to follow the deformation. Using the conductive thread approach, no additional step after manufacturing of the fabric is required to establish conductivity. The conductivity of these threads lies in the range of 10–500 Ω/m (Locher, 2006).

In order to evaluate the resistance shift during a stretching test, generally the measurements are performed with a strain tester, such as Zwick/Z010. The sample yarn is linked and simultaneously connected with a digital multimeter for an analog measurement, or with a microcontroller/read-out circuit in the case of a digital one (Schwarz et al., 2011b). Oh et al. (2003) adopted the conductivity (S/cm) variation as an electrical parameter in relation to elongation. The changes of mechanical properties of the conductive yarns were investigated with a tensile testing machine by a standard test method (ASTM D 751-95) coupled with a digital multimeter. Other evaluations with this experimental setup are focused on aging and hysteresis properties of the material (Guo and Berglin, 2009).

A mixture of staple fiber materials and a certain amount of electrically conductive staple fibers can be mixed and spun into the yarn to achieve the electrical conductivity required. Depending on the metal content, these yarns have, more or less, textile and metallic properties at the same time. Adding only a small percentage of electrically conductive fibers, the result is antistatic clothing, featuring low conductive properties (McCann, 2013).

Blum (2000) describes the manufacturing of a composite yarn of textile roving and monofilament metal thread. During the yarn-spinning process on a ring spinner, a coated metal wire is added centrally to the roving. In the thermal treatment following the spinning process, the melting coating adheres the central wire to the spun textile sheathing. The main issue with this process is the stiffness of the yarns. Moreover, during the manufacturing process of the conductive fabric, a precise position of the conductive yarns within the fabric is not predictable. The helical path around the yarn involves this issue. In terms of electric conductance, this method allows production of fabric features with about 17.8 Ω/m (Cottet et al., 2003).

Another method of achieving conductivity is coating yarns with a metal layer. Adopting an electrochemical process, a fine metal layer such as copper (Cu), silver (Ag), or gold (Au) can be deposited on the surface of the fibers (Schwarz et al., 2009). The advantage of this technique is the low electrical resistance about 50 Ω/m. On the other hand, usually the disadvantage regards the mechanical propriety, because the metallic coating is sensitive to breakage during the deformation of the yarn or during the textile production process. To solve this issue Schwarz et al. (2011b) applied the hollow spindle technology to produce electroconductive and elastic yarns, with enhanced elastic and stable electrical–mechanical properties after exposure to cyclic straining and washing. Fig. 4.3D shows the design of the conductive yarn produced by the hollow spindle process used for washing and stretching tests.

The electrical resistance remains constant (<4 Ω/m for conductive yarns based on copper) over elongation levels up to 100%, and after 25 washing cycles, only the silver-based yarns do not change their electrical resistance. The yarns with the same structure, but based on copper and stainless steel, show an increase in their resistance after the washing test (Schwarz et al., 2011a). The stainless steel and copper yarns were evaluated by quantifying their electrical resistances stability before and after washing with four-point probe techniques. This method is typically used to measure electrical resistance of a thin film or diffusion layer on an insulating material (Schroder, 2006) and the experiments have been carried out with the following setup:

- voltmeter (Keithley 195A Digital Multimeter with resolution of 0.001 mV);
- amperometer (Solartron Schlumberger 7150 Plus Digital Multimeter with resolution of 0.1 mA);
- DC current source (RS PL-series).

The washing tests followed the International Standard ISO 6330:2000 (Washing, 2000) procedure with a Wascator FOM71 CLS washing machine.

As an intermediate approach, introduced by the development of nanotechnologies and their application to the e-textile field, there is the coating of fibers (cotton, polyester, and nylon) with silver nanowires (Ag NWs), in other words, huge aspect ratio monocrystalline silver filaments, typically 15 μm in length and 35 nm in diameter. By properly coating the textile fibers by means of a net of NWs, and annealing them at 150°C for 15 min, one obtains a partial sinterization of the network and the formation of conduction bridges across the NWs. This allows the realization of a conformal, partially transparent, though and flexible coating that is able to convey electrical signals/energy, reaching 8 Ω/m able to survive to 200 bend cycles and to have unchanged properties after 5 washing cycles (see Fig. 4.4) (Atwa et al., 2015).

Moving to the next integration level, we consider that weaving, stitching, and embroidery of conducting yarns in or on the fabric are currently used to achieve electrical properties. In principle, standard manufacturing methods are used to incorporate the conducting yarn in the textile, such as:

- manually attaching conventional wires or sewing conductive thread (Orth, 2002), the yarn is added by guiding it with a needle through the textile;
- machine embroidering of conductive thread (Post et al., 2000), in which the yarn is fixed on the surface of the textile by a separate thread;
- replacing nonconductive fibers with conductive ones (Nakad, 2003).

In these methods, the conductive yarn is thus applied after the textile has been made, or even after the product has received its actual shape. Instead, with a weaving on a loom, the conducting yarn is woven simultaneously with the entire textile.

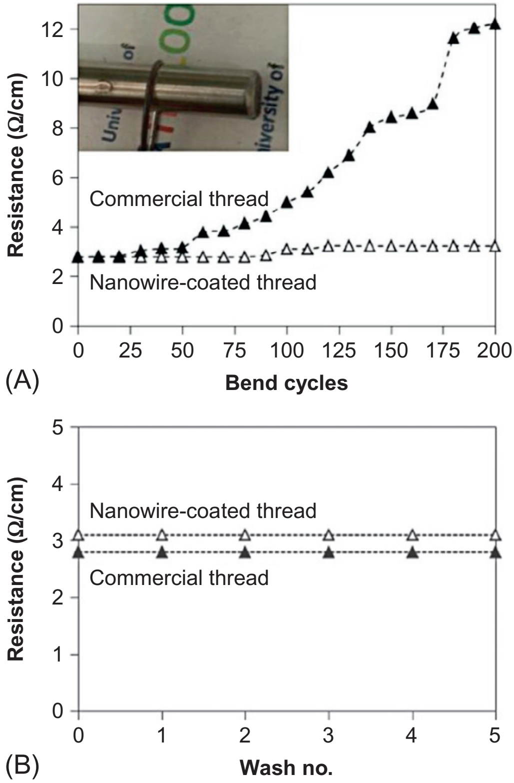


Fig. 4.4 Resistance of a NW-coated nylon thread and commercially available conductive thread after cycling of repeated bends over a 6 mm radius of curvature (A) and of repeated washings (B).
From Atwa, Y., Maheshwari, N., Goldthorpe, I.A., 2015. Silver nanowire coated threads for electrically conductive textiles. J. Mater. Chem. C3, 3908

In principle, the textiles are meant to be worn, washed, stored, and folded, thus the improvement of the electronic textiles shall not affect the original properties. In particular, breaking points between electric components and conductive yarn, or changes of the electrical property of the conductive yarn after mechanical stress, are taken into account. Fig. 4.5 depicts the electrical and mechanical response of a single conducting yarn, compared with a single fabric sample (nonconducting multifilament threads based on polyester) as a function of the strain applied, where de Vries and Peerlings (2014) showed that mechanical failure precedes electrical failure. Moreover, the researchers observed a change of the strains' characteristic due to the weaving pattern.

The British company Baltex uses the knitting technology to incorporate metal wires in textile structures. Their fabrics, which they commercialize under the name Feratec®, can be used mainly for two purposes, namely "heatable" textiles and electromagnetic shielding materials (Baltex, 2014).

The Danish company Ohmatex develops weaving electronics into fabrics, electronic conductors in clothing, operating panels in textiles (soft keyboards, displays,

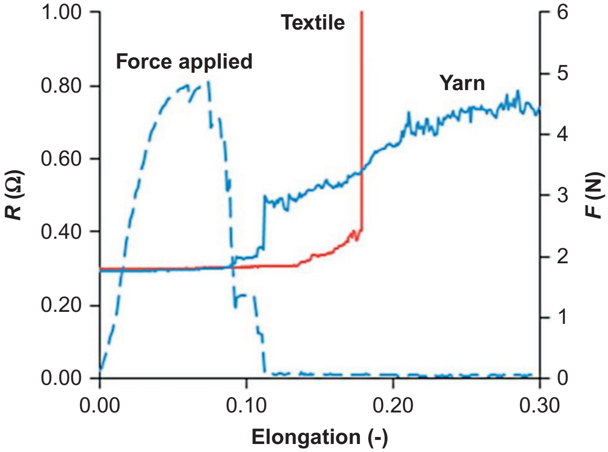


Fig. 4.5 Comparison between the resistance of conductive yarn and a textile sample versus elongation. Blue dashed line shows the force applied to both wires during the elongation phase. From De Vries, H., Peerlings, R., 2014. Predicting conducting yarn failure in woven electronic textiles. Microelectron. Reliab. 54 (12), 2956–2960.

etc.) and microsensors. The conductive yarn that they use is a copper thread, plated with a silver layer and coated with polyester (Ohmatex, 2015).

4.2.3 Conductive inks

Conductive coating is an extrinsic alteration to the fabric substrates and it can be achieved by conductive inks.

It should be specified that the conductive inks must contain an appropriate highly conductive metal precursor such as Ag, Cu, or Au nanoparticles (NPs), alloys of the cited metals, core/shell systems, and a carrier vehicle. Most of them are water based. These specialized inks can be printed onto various materials, among them textiles, to create electrically active patterns (Stoppa and Chiolerio, 2014).

In term of manufacturing process, sheet-based inkjet and screen printing are the best for low-volume, high-precision work and they allow printing of conductive material on different substrates, such as natural or synthetic fabric.

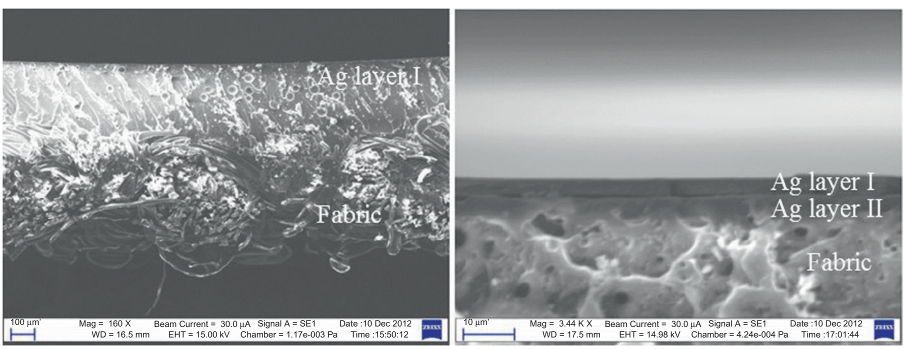
The inkjet technique is flexible and versatile, and can be set up with relatively low effort (Parashkov et al., 2005). It requires minimal material consumption, and it's not necessary to wear a mask. The technique is an additive process without chemical etching and pollutant agents.

However, to obtain a high performance conductive strip via inkjet printing, some technical aspects need to be considered. The conducting layers can be very thin, about 1 μm, requiring measurement with a scanning electron microscope (SEM) and not with a simple rugosimeter or profilometer, and hence, the rough, uneven, and porous surface of the fabric can be an issue (Merilampi et al., 2010). The ink is deposited via droplets and the viscosity is a significant parameter to be considered, because organic or inorganic inks, with dielectric or metal particles dispersed, can clog the nozzle. To overcome this issue, adopting a multiple nozzle system and a prestructured substrate, the resolution and productivity are improved (Blayo and Pineaux, 2005). Also to limit clogging, the dispersed particles should be smaller than one-tenth of the nozzle diameter, as a rule of thumb.

The conductive inks allow a uniform and flat conductive coating on the textile, however, the coating can affect the mechanical properties of the fabrics in terms of tensile, shear, and bending properties (Farboodmanesh et al., 2005) due to the change in yarn mobility after the coating is applied. These changes depend on the viscosity, uniformity, porosity, and flexural rigidity of the conductive material (Dubrovski and Cebasek, 2005). Inks may also contain additives which are used to tune or to add specific ink properties (Tiberto et al., 2013), thus increasing performance in relation to the final application (Perelshtein et al., 2008).

In comparison to a standard substrate for electrical purposes (eg, FR4, polyimide, etc.), a fabric has a roughness surface that can affect the electrical properties of the electrical coating made by inkjet printing. Chauraya et al. (2013) developed a wearable antenna using inkjet printing with the aim of overcoming the problem related to the nonuniform textile surface. They printed two silver layers with a thickness of 3 μm on the stretchable fabric, with a subsequent curing process. One of the two conductive silver layers was chosen as an "interface layer" with the polyester cotton fabric, and the other one was used to improve the conductivity and the pattern definition. Fig. 4.6 shows a cross-section of the yarn, illustrating the layer separation. A thin and uniform intermediate layer allows the yarn to overcome the nonuniform textile surface issue. This layer turns out to be the new surface of the fabric.

Generally, using the inkjet printing techniques, the inks should respect the following requirements (Stassi et al., 2014):



(A) (B)

Fig. 4.6 SEM images of printed layers: (A) the interface layer and (B) the inkjet printed layer. From Chauraya, A., et al., 2013. Inkjet printed dipole antennas on textiles for wearable communications. Microw. Antennas Propag. 7 (9), 760–767.

- high electrical conductivity;
- resistance to oxidation;
- dry out without clogging the nozzle during printing;
- good adhesion to the substrate;
- lower particle aggregation;
- suitable viscosity and surface tension.

After inkjet printing of a metal NP-based ink, in order to form a conductive printed pattern, particles must be sintered to create continuous connectivity between them and obtain electrical percolation (for a detailed discussion on sinterization see Chiolerio et al., 2012). Sintering is the process of welding particles together at temperatures below the corresponding bulk metal melting point, involving surface diffusion phenomena rather than phase change between the solid and the liquid. For instance, with inks based on gold NPs (~1.5 nm diameter), the melting temperature was experimentally found to be as low as 380°C, while for inks based on silver NPs (15–20 nm in diameter), a complete sintering can be obtained down to 180°C (Camarchia et al., 2014).

Screen printing is another appropriate technique to develop e-textiles using conducting inks. As shown in Fig. 4.7A, the screen printing procedure, based on a stencil process, comprises the printing of a viscous paste through a patterned fabric screen and is usually followed by a drying process. This allows the ink to develop a pattern and thick layers from pastelike materials. Screen printing also makes integration with planar electronics simpler than with conductive yarn systems. This method can be applied to flat or cylindrical substrates with a resolution of the conductive line lower than 100 μm. By optimizing process, conditions, and materials, the resolution may decrease to 30 μm line/space on thin, flexible substrates (Numakura, 2008). Moreover, screen printing can use inks based on organic semiconductors, and can be printed with a curing temperature of 100°C for PEDOT:PSS (Ionescu et al., 2012).

Although inkjet and screen printing are versatile, they do have their limits. During the printing process, one limit of the silver paste is the thickness. To achieve high

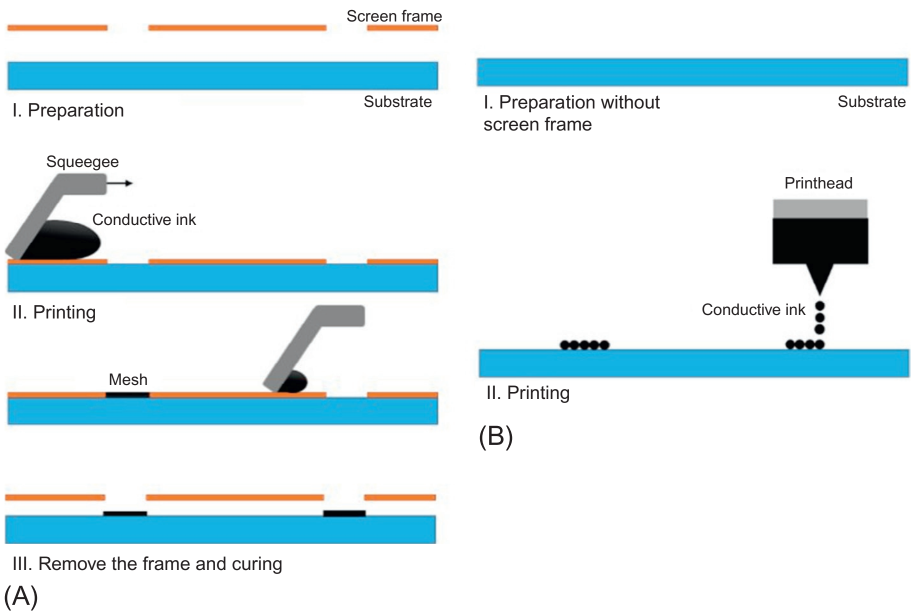


Fig. 4.7 Comparison between (A) screen printing and (B) inkjet printing process.

conductivity and uniformity of the printed line, it is necessary to apply several passes (overprints), decreasing the electrical resistivity as shown in Fig. 4.8. After five printing passes the result is better ink penetration of the fabric. The measurements have been conducted for each printing pass by using time domain reflectometry (TDR) measurements.

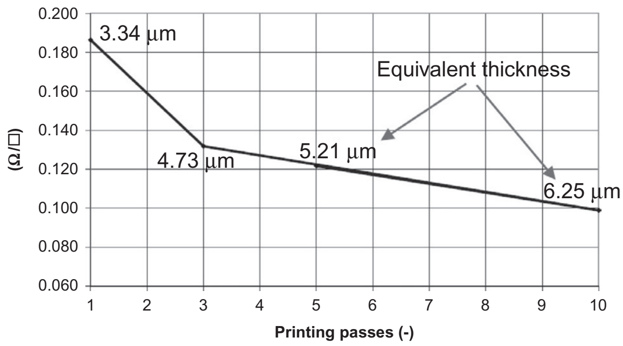


Fig. 4.8 Electrical resistivity versus printing passes highlighting the thickness obtained.
From Locher, I., 2006. Technologies for System-on-Textile Integration. Available at: http://e-collection.library.ethz.ch/view/eth:28457 (accessed 20.01.14).

In addition, several passes affect the mechanical properties, and risk interrupting the electrical conductivity with creasing of the fabric. Fig. 4.9 shows the conductivity changes for the number of creasing interactions with two different thickness levels (Locher, 2006).

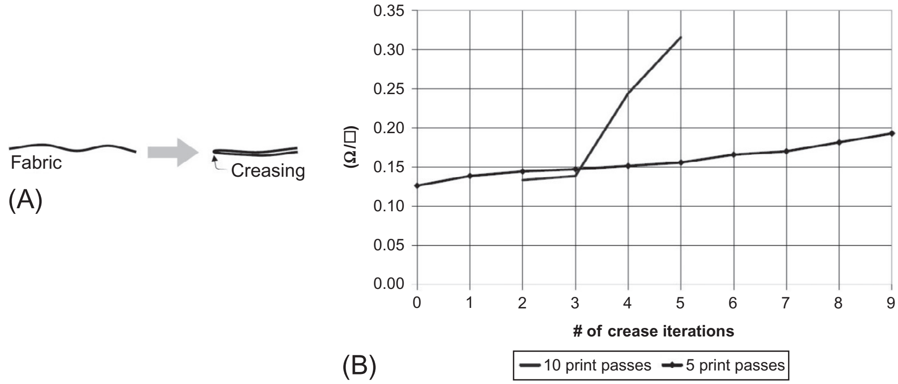


Fig. 4.9 (A) Creasing of the fabric with printed transmission lines; (B) DC resistance changes versus number of creasing iterations.
From Locher, I., 2006. Technologies for System-on-Textile Integration. Available at: http://e-collection.library.ethz.ch/view/eth:28457 (accessed 20.01.14).

A group of researchers of Istituto Italiano di Tecnologia—Center for Space Human Robotics, Politecnico di Torino—Applied Science and Technology Department, in collaboration with a spin-off company, Politronica Inkjet Printing, developed a high-density surface EMG (HD-sEMG) sensor matrix by inkjet printing with a silver NP-based ink on a flexible polyimide substrate. In terms of electrode-skin contact impedance, the results obtained are comparable with commercial electrodes (Scalisi et al., 2015). The HD-sEMG matrix in Fig. 4.10 shows the flexibility of the manufactured electrode matrix (8 × 8), with a diameter of a single electrode of about 8 mm; the high-surface area is achieved using a nanocomposite ink. The results show an intrinsic impedance of the newly printed electrodes of roughly 20 Ω, compared with commercial electrodes that resulted in about 2 Ω of impedance. The tests have been carried out with the Potentiostat 700D CH instruments in order to measure the impedance of the electrodes in their dry conditions on eight different subjects. The impedance of the electrodes in their usage was tested between 10 and 1000 Hz.

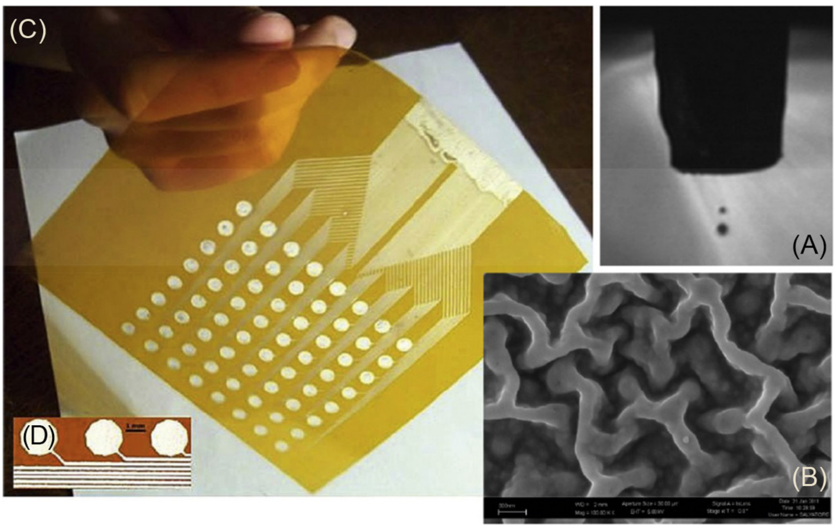


Fig. 4.10 Inkjet printing of the pattern: (A) Ag NP ink droplet ejected by the nozzle. (B) Surface of the nanocomposite ink after solvent removal, showing a high specific area. (C) Flexible electrode 8 × 8 matrix printed on polyimide foil after thermal and insulation treatments. (D) Optical micrograph of some Ag lines (width ~0.5 mm) and electrodes (diameter 8 mm).
From Scalisi, R.G., et al., 2015. Inkjet printed flexible electrodes for surface electromyography. Org. Electron. 18, 89–94.

Remaining in the physiological monitoring field, the National Textile Center at North Carolina State University (Raleigh, NC, USA) developed a garment able to measure ECG, heart rate, respiration, and temperature. They adopted conductive ink to develop the sensors and the conductive line inside a common garment. The electric circuit was printed on nonwoven fabric and different conductive inks were tested, such as Evolon® by Freudenberg KG, Tyvek® by DuPont™, FiberWeb Resolution™ Print Media by BBA FiberWeb™, Precisia LLC and Creative Materials Inc. (Karaguzel et al., 2009), during washing trials. Fig. 4.11 depicts the impedance values of three

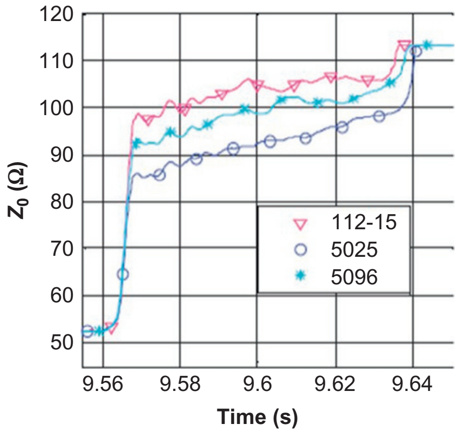


Fig. 4.11 Three different conductive inks (CMI 112-15, DuPont 5025, DuPont 5096), with a similar sheet resistivity (~0.01 Ω/sq./mil), show different impedance value after five washing cycles.
From Karaguzel, B., et al., 2009. Flexible, durable printed electrical circuits. J. Text. Inst. 100 (1), 1–9. Available at: http://dx.doi.org/10.1080/00405000802390147 (accessed 09.01.14).

different conductive inks after five washing cycles. The electrical properties of the printed lines were tested before and after washing, determining the characteristic impedance of the 10 cm long coplanar waveguide lines (CPW) using a Tektronix 11801 B Digital Sampling Oscilloscope in TDR mode. The probe was placed on the CPW while the other end of the line was left open during measurements. DC resistance of the transmission lines was measured using a digital Fluke 77/BN Multimeter.

4.2.4 Planar fabric circuit board

Several research results report the integration of electronics with textiles, however the next step of integration regards the IC components with fabric. For instance, Jung et al. (2003) and Post et al. (2000) placed a silicon chip on a flexible plastic board on a fabric, which resulted in a stiff feeling in the clothes due to the flexible silicon board (eg, Kapton®), in addition to the long integration process and the durability.

Planar thin-film technology is applied directly on the fabric to develop a FCB. It allows the implementation of a circuit board on a plain fabric patch for wearable electronic applications. It features a soft and flexible impression, just as normal clothes do.

Silk screening of conductive epoxy or gold (Au) sputtering technique allows the deposition of planar conductive lines directly on the fabric patch. First, the circuit board is silkscreen printed on the fabric, then the IC is wire-bonded to the patterned electrodes or other components. Finally, the IC is molded with nonconductive epoxy, improving the mechanical properties in the welding points (Kim et al., 2008). For the integrity of the package with the fabrics, the tensile strength test is performed by straining the planar fabric circuit board (P-FCB) along the *x*-direction, *y*-direction, and the diagonal direction. The maximum load is 85.1 N/cm in the *x*-direction, 85.2 N/cm in the *y*-direction and 99.3 N/cm in the diagonal direction, otherwise the result is a breaking of the bonding or welding points.

The measured sheet resistance of the silk screen pattern on the fabric (cotton) ranges between 0.01 and 60 mΩ/m, as measured by a standard four-point probe. This value remains unchanged after 50 washing cycles (Kim et al., 2010). The resistance measurement yielded results of the proposed via and conductive adhesive and the frequency response of a P-FCB transmission line (15 cm long and 1 mm wide). Its bandwidth is 80 MHz, and this is sufficient to deal with biosignal processing. The analyses were performed with a vector network analyzer (Lee et al., 2010). To get an average value, as many as 100 connections were formed and measured. The resistances of the proposed via and conductive adhesive measured 0.24 and 0.34 W, respectively (Kim et al., 2010).

Researchers at the Electronics Department and the Wearable Computing Laboratory at the ETH in Zürich demonstrated another approach to develop a fabric circuit board. They started from a plain woven textile structure consisting of polyester (PET) monofilament yarn twisted with copper thread and they developed a hybrid fabric called PETEX (Locher, 2006). In detail, PET yarns have a diameter of 42 μm and copper alloy wires have ~50 μm (Fig. 4.12A).

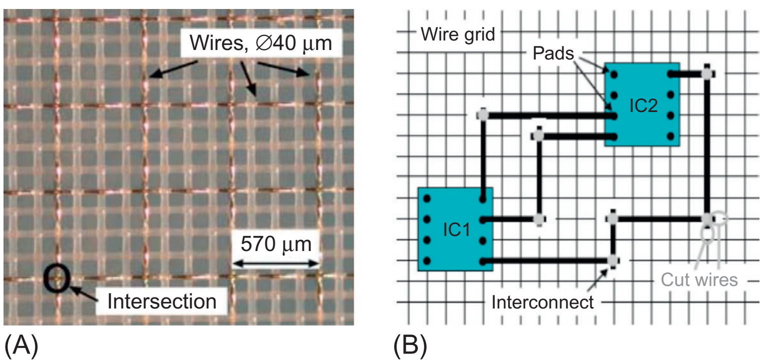


Fig. 4.12 (A) PETEX and (B) method to integrate circuits in a PETEX structure.
From Locher, I., 2006. Technologies for System-on-Textile Integration. Available at: http://e-collection.library.ethz.ch/view/eth:28457 (accessed 20.01.14).

Developing an ad hoc structure, they were able to design a custom textile circuit, as shown in Fig. 4.12B. Generally, the fabric has a regular structure (warp and weft), however in microscale it is not possible to obtain a geometric repeatability of the position of the contact point between the conductive fibers, as shown in Fig. 4.13. This issue, appreciable with a common optical microscope tool, becomes critical when an electrical component needs to be soldered on the e-textile.

4.2.5 Textile sensors

In recent decades a significant breakthrough has been achieved in exploring and enhancing capabilities of textiles in response to environmental stimuli (Castano and Flatau, 2014).

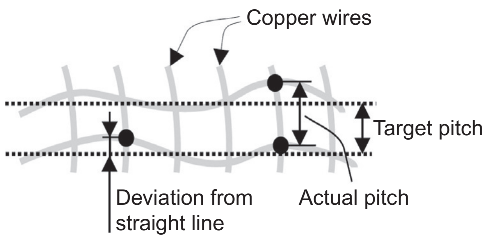


Fig. 4.13 Misalignment of the contact points with the target pitch.
From Locher, I., 2006. Technologies for System-on-Textile Integration. Available at: http://e-collection.library.ethz.ch/view/eth:28457 (accessed 20.01.14).

Conductive textiles that change their electrical properties as a result of the environmental impact can be used as sensors. Smart textiles possess the properties of conventional textile materials and carry additive functional values. Typical examples are textiles that react to deformations such as pressure sensors, stretch sensors, and breathing sensors. Different physical principles are adopted to reach the same purpose, such as capacitive or resistive behavior of the textile sensor. On the other hand, biochemical, optical, temperature, humidity, and biopotential sensors can be made with smart textiles.

4.2.5.1 Pressure sensors

The localized detection or distributed pressure, integrated into textiles and clothes, has been exploited in several application fields (Ashruf, 2002). In healthcare and sports, pressure sensors embedded in shoes enable the analysis of gait. Piezoresistive sensors have also been applied to car safety belts for monitoring cardiorespiratory patterns in subjects (Hamdani and Fernando, 2015). Rehabilitation, for example, after a stroke, requires the controlled motion of limbs; pressure sensors attached to the corresponding muscles monitor their activities and behavior (Lukowicz et al., 2006). To prevent pressure sores (decubitus), pressure sensors can supervise vulnerable body regions, allowing the timely feedback to the wearer (Axisa et al., 2005). Generally these sensors are made with a coating of composite comprising CP, PDMS, and silicone in a knitted fabric (Wang et al., 2014).

Tactile sensing applications are usually used in capacitive fabrics. Their electrical behavior depends on the material sensing composition and on the read-out circuit used. Generally, fabric capacitors consist of two different electrode plates separated by dielectric material, as shown in Fig. 4.14 (Guo et al., 2014). The conductive part, that is, the electrode, can be sewn (Holleczek et al., 2010), woven (Takamatsu et al., 2012), embroidered (Takamatsu et al., 2012) in case of conductive thread, or can be painted, if the conductive material is an ink (Sergio et al., 2003). The dielectrics materials are usually synthetic foams, fabric spacers, or polymers. In principle, a pressure applied on the sensing part generates capacitance variations or a changing of the piezoelectric resonance frequency. For capacitive sensors, a change in parasitic capacitance and resistance can be compensated for by the electronics, therefore the wiring has a marginal influence on the sensed signal. Moreover, the sensor capacitors can be placed in arrays achieving a matrix and distributed pressure sensor. For instance, Meyer et al. (2006)

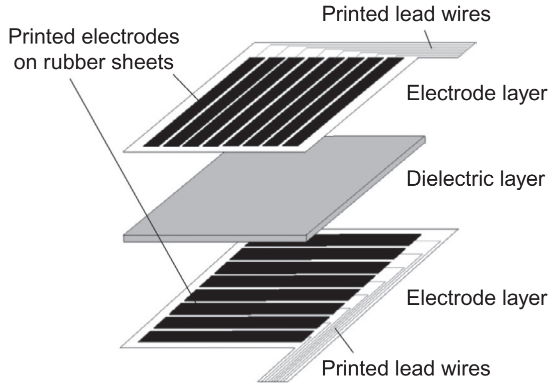


Fig. 4.14 The electrodes on the two-electrode layers are oriented orthogonally and each crossing point of the two perpendicular electrode arrays makes up a capacitive sensor cell on the sheet.
From Guo, S., et al., 2014. A two-ply polymer-based flexible tactile sensor sheet using electric capacitance. Sensors 14 (2), 2225–2238.

integrated a matrix with several capacitive pressure sensors into a garment to detect muscle activity on the upper arm. Xu et al. (2013) instead used a pressure sensor array to analyze the sitting posture for clinical purposes.

Adopting a resistive approach, the pressure sensors, made by a grid of intersecting embroidered conductive yarns, change the contact resistance of intersecting yarns when a pressure is applied. The same result can be achieved using conductive elastic yarns (Wang et al., 2011). They are integrated in a "textile chamber" in which changing the geometry of the sensing material after pressure causes it to respond with an electrical resistance variation. In term of pressure, the sensitivity obtained is about 3 Pa with a pressure range of 0–2 MPa. Fig. 4.15 depicts the working principle in which the teeth geometry of the top and bottom layers deforms the sensing fabric, changing its intrinsic electrical properties.

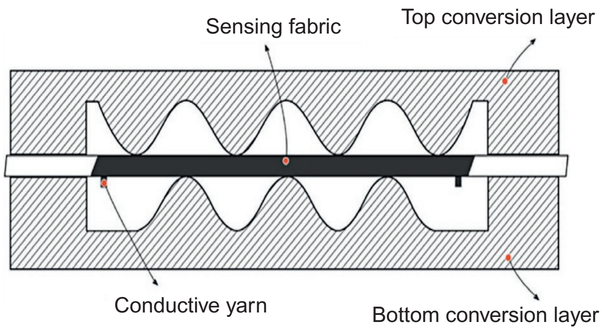


Fig. 4.15 Tooth-structured resistive fabric pressure sensor.
From Wang, Y., et al., 2011. Novel fabric pressure sensors: design, fabrication, and characterization. Smart Mater. Struct. 20 (6), 65015.

This kind of sensor can be manufactured at different levels, that is, fiber, yarn, or coating. In particular, foams can be pressure sensitive thanks to an additional surface coating realized by means of conducting inks which can change their conductance during a contact event (Brady et al., 2005).

The team of the Center for Micro-Bio Robotics of Istituto Italiano di Tecnologia (Pisa, Italy) produced a composite capacitive three-axial sensor based entirely on commercial conductive fabrics, demonstrating its high compliance and stability under manipulation (Viry et al., 2014).

Characterization: Surface morphologies were examined using a JEOL JSM-7001F field emission SEM and the FTIR spectrum was measured with a Bruker Vertex 70 FT-IR spectrometer. The weight fraction of silver in the conductive fiber was evaluated using a thermogravimetry analysis (Q50, TA Instruments) and a mechanical strength test was conducted using USTER TENSORAPID 4. Capacitance measurements were conducted at 300 kHz frequency with a 1 V AC signal using an Agilent E4980A, Precision 3 LCR Meter. The force and its frequency were mainly controlled by a universal manipulator of Teraleader with 0.01 N resolution.

Lee et al. (2015) described a textile-based pressure sensor with high sensitivity (0.21–1 kPa), stability (against 3000 bending tests), a fast response, and a relaxation time provided with a universal manipulator of Teraleader with 0.01 N resolution coupled with an Agilent E4980A (300 kHz, 1 V AC signal). The textile was based on highly conductive fibers coated (0.00015 Ω/m) with dielectric rubber materials. The conductive fibers were fabricated by coating poly (styrene-butadiene-styrene) (SBS) polymer on the surface of poly(*p*-phenylene terephthalamide) (Kevlar) fiber, followed by converting a huge amount of silver (Ag) ions (80 wt%) into Ag NPs directly in the SBS polymer (Fig. 4.16).

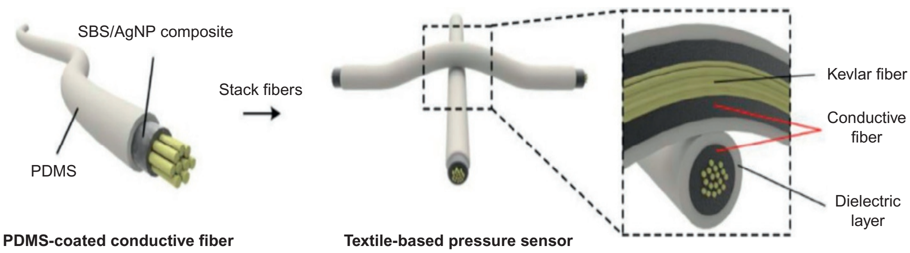


Fig. 4.16 Schematic illustration of the fabrication of the pressure sensor from a single sensing fiber to their implementation.
From Lee, J., et al., 2015. Conductive fiber-based ultrasensitive textile pressure sensor for wearable electronics. Adv. Mater. 27 (15), 2433–2439.

4.2.5.2 *Strain sensors*

Fabric strain sensors are textile structures that are able to have an electrical response following a mechanical strain. It is possible to design fabric strain sensors at different levels of the structure hierarchy: overlapping of sensing fibers with nonsensing fibers (Araki et al., 2012), adding sensing yarn into fabric (Huang et al., 2008) or coating the fabric with a strain sensor material (Calvert et al., 2008). As occurs for pressure sensors, an ad hoc read-out circuit has to be designed.

In term of applications, wearable stretch sensors are mainly used for sensing and monitoring body parameters, as the textile is in contact with the skin over a large body area. This means that monitoring can take place at several locations on the body (Pacelli et al., 2006). A specific structure of textile sensors can be integrated fibers featuring piezoresistive (Huang et al., 2008), piezoelectric (Nilsson et al., 2013), or piezo capacitive (Koschan et al., 2006) properties, enabling their use as strain or deformation sensor.

According to the type of technologies used, conductive thread knitted into a fabric can be strained up to 65% (Wijesiriwardana et al., 2003). A fabric resistive strain gauge is made using an electroconductive elastomeric fiber (eg, carbon filled polymeric fibers) and nonconductive base fiber (which could be an elastomer). The base structure is formed using the nonconductive fiber and the conductive fiber is laid in the course direction of the base structure. This configuration allows an electrical resistance variation due to the stretching of the fabric. When the strain gauge is stretched in *Y* (courses) direction by using planar loads, the electrical resistance increases. This is due to the piezoresistive behavior of the composite elastomer (Taya et al., 1998). However, when the strain gauge was stretched in the *X* (wales) direction, an insignificant variation of the electrical resistance was observed due to the loss of curvature at bending regions. To evaluate this feature, a fiber meshed strain transducer was clamped between the crossbars of a tensile tester (INSTRON 5500) and the upper crossbar was programmed to carry out a dynamic extension of the transducer.

On the other hand, Zhang et al. (2006) developed a strain sensor with carbon fibers knitted reaching a maximum deformation of 30% under a high range of temperature (from 50°C to 200°C), considering that generally the strain gauges are very sensitive to temperature changes and hence require electronic compensation. The carbon fabrics were fabricated by carbonizing the stabilized carbon fabric at the maximum temperature of 1000°C in the inert atmosphere (nitrogen). The diameter of the fabric was about 5 mm and had 12 loops. The tubular structure has more contacting points, and larger internal frictions caused by contacting yarns in comparison to the single warped one. This allows restoration of the original configuration after elongation (see Fig. 4.17).

The experimental setup for the strain and electrical resistance measurements used simultaneously an Instron Universal Material Tester 4466 and a Keithley Multimeter. The researchers adopted a cycle test with a crosshead speed to a given maximum strain.

Stretchsense® developed a soft fabric stretch that transmits information via Bluetooth® about how much they are being stretched thanks to the electronic embedded at the end of the sensing strip (Fig. 4.18).

The Ohmatex Company weaves a very fine constantan (copper–nickel alloy consisting of 55% copper and 45% nickel, Davis et al., 2001) wire into a textile ribbon. This has been used in the Edema medical stocking for measuring changes in leg volume for heart failure patients. This textile ribbon can also be used to measure vibration in large structures such as wind turbine blades (Ohmatex, 2015).

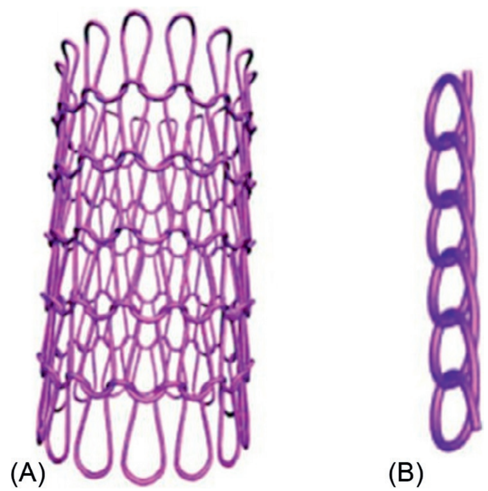


Fig. 4.17 (A) Tubular and (B) single wrap structure.
From Zhang, H., et al., 2006. Conductive knitted fabric as large-strain gauge under high temperature. Sensors Actuators A: Phys. 126 (1), 129–140.

Fig. 4.18 Soft fabric stretch made by Stretchsense®.
From Stretch Sense™.

4.2.5.3 Chemical and gas sensors

Fabrics capable of reacting following a chemical variation can be used as chemical and gas sensors. Relevant applications of these sensors can be found in safety equipment and environmental quality analysis (eg, the presence of harmful gases or water pollutants). To obtain these features, miniaturized chemical/gas sensors can be integrated into a fabric structure by stitching or sewing them. Otherwise, using a polymer coating such as PPy or PANI onto PET can fabricate toxic gas sensors (Hong et al., 2004). Using this method, the fabric sensors are sensitive to the chemical environment variation with a shift of the electric resistance. The specific chemical variation monitored depends on the properties of the sensing film exposed. For instance, PEDOT nanotubes are suitable for monitoring concentration levels of nitric oxide (NO) (Lu et al., 2008). Fig. 4.22 shows two different works about humidity sensors, and in particular, Fig. 4.19A shows a quasi-linear variation of the electric resistance of PEDOT-PSS coated fibers (Windmiller and Wang, 2013) and Fig. 4.19B shows a capacitance variation versus humidity using different sensitive polymeric ink thicknesses (Daoud et al., 2005).

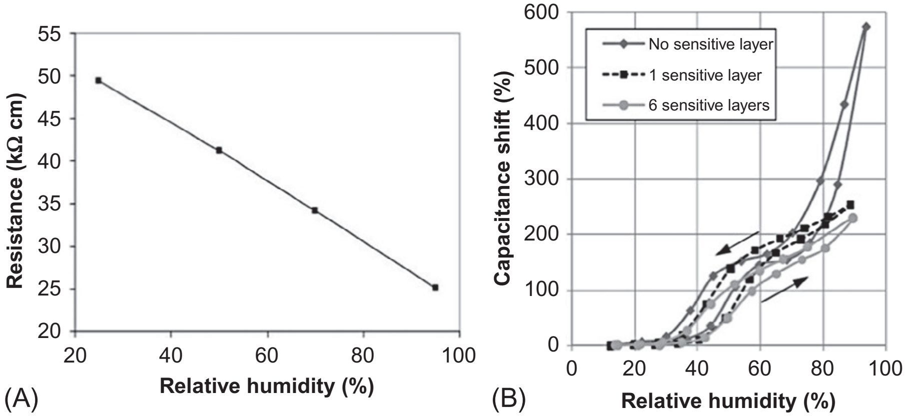


Fig. 4.19 (A) Electric resistance trend from 25% to near humidity saturation. (B) Electric capacitive variation using different sensitive ink layers thicknesses and unmodified polyimide substrate (no sensitive layer).
From Daoud, W.A., Xin, J.H., Szeto, Y.S., 2005. Polyethylenedioxythiophene coatings for humidity, temperature and strain sensing polyamide fibers. Sensors Actuators B: Chem. 109 (2), 329–333.

In terms of biosensing, recent insights into novel fabrication methodologies and electrochemical techniques have shown chemical sensors able to augment conventional physical measurements (ie, heart rate, EEG, ECG, etc.) (Windmiller and Wang, 2013).

BIOTEX, an EU-funded project, aims at developing dedicated biochemical-sensing techniques compatible with integration into textiles. The goal was to monitor the body fluids via sensor distributed on a textile substrate and performing biochemical measurements. The approach involves the development of sensing patches adapted to different body fluids and biological species to be monitored, where the textile itself is the sensor (Coyle et al., 2010).

The researchers of the National Centre for Sensor Research, Dublin City University (Ireland), developed chemical sensors able to measure and analyze sweat in real time on the body. They designed a microchip version of the platform to measure changes in the pH of sweat. The color change of the pH sensitive fabric was detected by placing a surface mount LED and photodiode module on either side of the chip, aligned with the pH sensitive fabric. The final device (180 μm thick) is flexible and can adapt to the body (Benito-Lopez et al., 2009).

4.2.6 Textile energy harvesting systems

Generally, e-textile technology hosts several electronic components, such as sensors, read-out circuits and embedded communication systems. All of them need to be powered, and batteries, or external power supply links, are a limitation for a wearable system. Mechanical stability, bulkiness, and lifetime are only some negative aspects of using an external energy source (Nishide, 2008). For these reasons, the wearable systems should be capable of harvesting energy dissipated by the human body, as motion, muscle stretching, thermal flow or biochemical variations.

Our body is a perfect energy source for wearable devices, and in particular, some daily actions, such as body motion, can generate enough energy to power sensors and/or wearable electronic components. Table 4.2 shows an average of the available power for bodily activities of human beings (Wang, 2008). Wearable electronic devices designed in micro (MEMS) and nanoscale (NEMS) may be powered by the human body, because the energy required is very low. For instance, Infineon is currently trying to recover energy by body movements to feed Mp3 players integrated in a jacket using piezoelectric materials (Infineon, 2015).

The piezoelectric effect is a feasible technique for converting mechanical energy from vibrations to electricity (Nilsson et al., 2014) reaching about 0.7 mW of power from the fibers in the textile. This effect is usefully exploitable with polymeric piezoelectric materials, such as polyvinylidene fluoride and its copolymer, because they are naturally flexible, lightweight, biocompatible and suitable for energy harvesting (Cha et al., 2011). The main issue with the human body interaction is the typical low frequency of mechanical motion (<10 Hz), leading to a low power harvesting.

On the other hand, the body temperature is another exploitable energy source. Feinaeugle et al. (2013) used a fiber-based thermoelectric power generator fabricated by evaporating thin Ni–Ag films on flexible textile substrates and they demonstrated a maximum power harvesting of 2 nW. Semiconductor nanowires exhibit promise for thermoelectric properties, but new, advanced fabrication techniques need to be developed.

Another technology is represented by solar clothing, in which the solar energy is harvested through a new generation of flexible solar cells (Lee et al., 2013). Integration of flexible solar cells into clothing can provide power for portable electronic devices.

Table 4.2 Available power generated daily by human body activities for a 68 kg adult (Wang, 2008)

Energy source	Available power
Footfalls	67 W
Arm motion	60 W
Body heat	2.4–4.8 W
Exhalation	1 W
Blood pressure	0.93 W
Breathing band	0.83 W
Finger motion	6.9–19 mW

Nowadays, the energy demand of portable devices is low enough that clothing-integrated solar cells can power most mobile electronics (Schubert and Werner, 2006).

Enabling textile energy storage requires that the textiles have good electrical conductivity. Flexible energy-storage devices have attracted attention in recent years due to their promising integrability into stretchable and wearable electronics (Hu et al., 2012a). In particular, supercapacitors are of significant interest as energy-storage devices associated with their high power density, long cycling life, and short charging time (Aegerter and Mennig, 2004). Recently, researchers developed a solution-based technique to convert cotton textiles into conductive textiles by coating the cellulose fibers with CNTs (Hu et al., 2010) or graphene (Yu et al., 2011) thin films. The three-dimensional (3D) high-surface-area characteristic of such textiles facilitates the access of electrolytes, enabling high electrochemical performance of textile supercapacitors. Bao and Li (2012) fabricated highly conductive and flexible activated carbon textiles (ACTs) by direct conversion of cotton textiles through:

1. dipping the cotton into 1 M NaF solution;
2. a drying process at 120°C for 3 h;
3. a curing process annealing the dried textiles in a horizontal tubular furnace at 800–1000°C for 1 h under vacuum and inert atmosphere conditions.

SEM analyses showed the textiles consisting of interwoven cellulose fibers with diameters ranging from 5 to 10 μm and a highly conductive under folding condition (sheet resistance ~1–2 Ω/m^2) measured via a Keysight Digital Multimeter. Furthermore, loading the fabric with MnO_2, cyclic voltammetry (CV) tests, a type of potentiodynamic electrochemical measurement, showed an improvement of the capacitance performance with a threefold increase in specific capacitance compared to that of ACTs. At the scan rate of 2 mV/s, the specific capacitance achieved was 269.5 F/g comparable with solution-processed graphene/MnO_2 textiles (Yu et al., 2011).

Jost et al. (2013) have developed textile supercapacitors based on knitted carbon fibers and activated carbon ink with capacitances around 0.51 F/cm at 10 mV/s. They used a solid electrolyte in place of a liquid electrolyte to reduce any possible leakage. The researchers also demonstrated the performance of the device when bent from 90 to 180 degree (Fig. 4.20) showing a small leakage of capacitance after a bending test of around 20%, typically a relevant issue for a supercapacitor. All experiments were carried out using a Biologic VMP3 potentiostat-galvanostat (BioLogic, USA). Devices were tested in a two-electrode symmetric setup and subjected to CV,

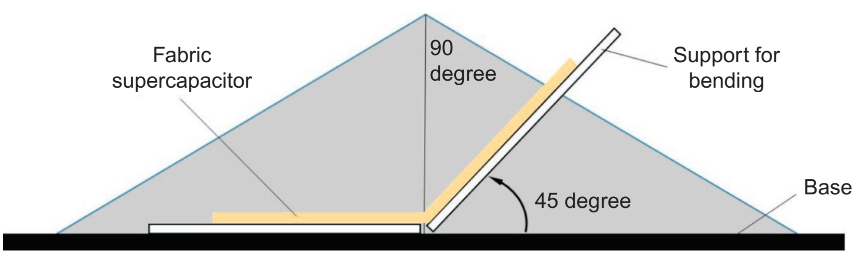


Fig. 4.20 Bending test experimental setup.

galvanostatic cycling, and electrochemical impedance spectroscopy measurements, following procedures fully described in previous studies. All devices were subjected to 100 pre-cycles at 20 mV s^{-1}, and values of capacitance and ESR were taken from tests after cycling.

They also tested the textile supercapacitor under 50% stretching and the result was a small loss in capacitance due to the breaking of the conductive network between carbon particles when changing the dimensions of the device.

On the other hand, compared with supercapacitors, Li-ion batteries have much higher energy density per weight. The concept of 3D battery electrodes has been used to enhance the capacitance (Long et al., 2004). In recent years, Hu et al. (2011) developed a Li-ion battery based on the conductive textiles in which the electrode materials are loaded into the 3D pores of conductive textiles. They found the stable potential range of conductive textiles in organic electrolytes, and effectively demonstrated a working Li-ion battery with a mass loading of ~168 mg/cm^2 and a thickness of ~600 µm. The textile conductor (sheet resistance of 8 Ω/sq.) is fabricated using a plain polyester fiber textile and well-dispersed single walled CNT ink in water with the addition of 1% sodium dodecylbenzenesulfonate. The conductive textile was found to be electrochemically stable in the voltage window of ~0.9–3.7 V. Either a Bio-Logic VMP3 battery tester or an MTI battery analyzer were used to perform the textile battery. The full cell was assembled and first cycled between 1.4 and 2.6 V for five cycles before the self-discharge test. The batteries were charged to 2.6 V and then disconnected for a certain period of time before a discharge full down to 1.4 V.

In a project funded by the Engineering and Physical Sciences Research Council (EPSRC), Researchers at the University of Southampton's School of Electronics and Computer Science (ECS) are developing an energy harvesting film in textiles using rapid printing processes and active printed inks (Wei et al., 2013).

Instead, Thermotron of UNITIKA Co. is a particular fabric able to convert sunlight into thermal energy while storing heat without wasting it. Inside the Thermotron there are microparticles of zirconium carbide which allow the fabric to absorb and filter sunlight. The inner layer of the fabric withholds the heat generated and prevents it from becoming lost, thus providing a salutary effect on the human body (Unitika LTD, 2015).

Finally, Cetemmsa Technological Centre is overseeing research projects in the use of sensors in sportswear and accessories. It is working on integrated power sources for added electronic functionality such as organic photovoltaic, as part of the EU-funded Dephotex project (Cetemmsa Technology Centre, 2015).

4.2.7 Wearable antennas

In recent years, the rapid progress on wearable devices has induced a significant development of wearable antennas, in order to stream the *body-data* information of the wearable sensors and making an autonomous wearable system. This technology is represented by the Wireless Body Area Network (WBAN), in other words, the wireless network of wearable computing devices. The WBAN has many possible applications in the medical field, where the sensors are in direct contact with human body and they stream physiological data in real time, for instance, to the internet. This methodology allows the access of patient data by medical professionals independent of the patient location (Yuce and Khan, 2011).

Wearable antennas, based on conductive textiles, exploit new flexible and smart structures without affecting the native textile properties (Giddens et al., 2012). To achieve this result, conductive textiles such as *Zelt*, *Flectron* and pure copper polyester fabrics are typically used as the radiating element, while nonconductive textiles are used as substrates (Rais et al., 2009). The geometry of an antenna developed for body wearable applications is shown in Fig. 4.21.

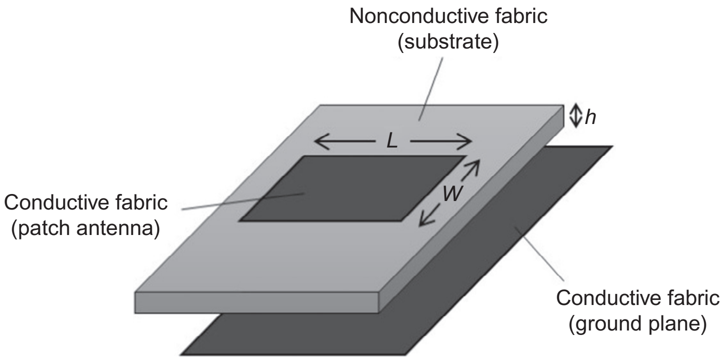


Fig. 4.21 Wearable antenna comprising a thin conductive fabric on an insulating fabric substrate backed by a ground plane.

Generally, body wearable antennas operate at frequencies ranging from 500 MHz to 5 GHz, allowing them to be physically small in construction and relatively simple to wear unobtrusively on the body. However, high frequency bands (>1 GHz) tend to have a very limited range and low wave propagation. The advantages of a high frequency antenna are that they are lightweight, small, and structurally strong (Matthews and Tittensor, 2014). On the other hand, using, for example, a wide band as an FM broadcast band (about 81–130 MHz), a wearable FM antenna should be designed without suffering from the detuning caused by the human body (Roh et al., 2010).

A microstrip patch is a representative candidate for a wearable integration, because it can be thin, lightweight, low maintenance, robust, and easily integrated into a garment and coupled with RF circuits (Wang et al., 2012). Moreover, the conductive textile used for antenna purposes has to have a low and stable electrical resistivity (<1 Ω/sq.) to minimize losses (Locher et al., 2006). Several properties of the materials can influence the behavior of the antenna properties. For instance, the permittivity and the thickness of the substrate change the bandwidth and the efficiency of a planar microstrip antenna (Liu et al., 2011). In general, fabrics present a complex structure, in term of density of fibers and hence air volume and size of the pores, which allow a very low dielectric constant with a reduction of the surface wave losses and an increase of the impedance bandwidth.

Dielectric properties of the nonconductive material play an important role. A wrong choice of material would compromise the performance of the antenna. The dielectric properties are affected by several physical parameters such as: temperature, moisture content, surface roughness, purity, and homogeneity of the material and signal frequency. The permittivity (ε) is a constitutive parameter of dielectrics and usually it is expressed by Eq. (5.2), where ε_0 is the permittivity of vacuum, 8.854×10^{-12} F/m (Baker-Jarvis et al., 2010) and ε_r can be expressed applied and the relative displacement.

$$\varepsilon_r : \varepsilon = \varepsilon_0 \cdot \varepsilon_r = \varepsilon_0 \cdot \left(\varepsilon_r' - \mathrm{j} \cdot \varepsilon_r''\right) \tag{5.2}$$

With a low dielectric constant, the surface wave losses are reduced and they are tied to guided wave propagation within substrate. Hence a low ε_r increases the spatial waves and the impedance bandwidth of the antenna (Salvado et al., 2012).

Generally, fabric dielectric properties are represented from the dielectric constant ε_r' and the ratio of the imaginary and to the real part, $\delta = \varepsilon_r'' / \varepsilon_r'$ (Stoppa and Chiolerio, 2014).

In addition, textile structures are composed of fibers, and each fiber can absorb a minimum quantity of water from the environmental moisture, increasing the dielectric constant. To counteract this effect, the antenna dielectric substrate is covered or treated superficially in order to protect the textile from the humidity or varying climatic condition (Hertleer et al., 2009).

Another issue regards the movement of the body that can change the geometry of the antenna and affect the antenna performance. In wearable systems, it is very difficult to keep the antenna flat all the time, especially when the antenna is made of textile materials. Moreover, the wearable antenna is bent frequently due to human body movements changing the electromagnetic properties of the antenna and affecting the data transmission. Sankaralingam and Gupta (2010) investigated the antenna's performance characteristics under bent conditions and they observed that due to bending, the resonant length of the antenna changed and hence, a shift of the resonant frequency occurred too. The tests were carried out by bending the polyester antenna around curved surfaces of cylindrical PVC pipes with different radii: 50.8, 63.5, 76.2, and 88.9 mm. These dimensions are comparable with different parts of the human body like an arm, leg, and shoulder. However, considering other parameters (input impedance bandwidth and input-reflection coefficient at the resonant frequency) there were no relevant changes during bending at different radii, as shown in Fig. 4.22. It is evident that these textile microstrip patch antennas may eventually replace patch antennas on standard printed circuit board substrates for various applications.

From a conductive fabric point of view, for a proper antenna design, the conductivity of the fabric (σ) is a relevant parameter. The conductivity is expressed in Siemens per meter (S/m) by Eq. (5.3):

$$\sigma = 1 / \left(\rho_s \cdot t\right) \tag{5.3}$$

where ρ_s is the surface resistivity and t is the thickness of the fabric. As descripted previously, at the microscale, the textile structure presents several discontinuities and these affect the current flow and the relative σ value (Ouyang et al., 2005).

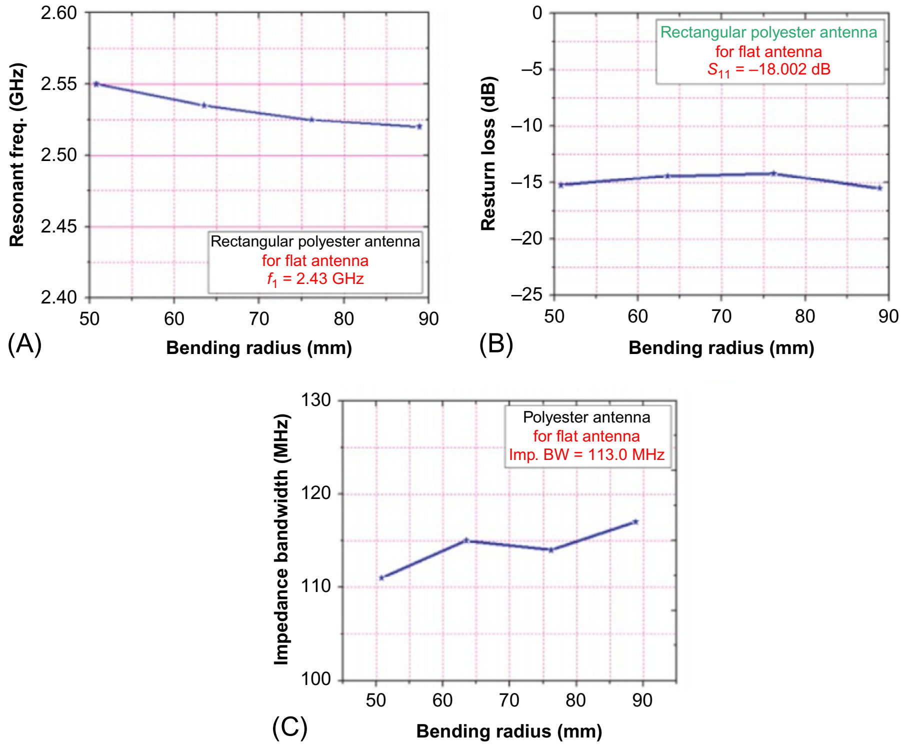


Fig. 4.22 Three different characterizations: (A) resonant frequency, (B) return loss, and (C) impedance bandwidth with different levels of bending radius using a textile antenna based on polyester.
From Sankaralingam, S., Gupta, B., 2010. Development of textile antennas for body wearable applications and investigations on their performance under bent conditions. Prog. Electromagn. Res. B 22, 53–71.

Research of Tampere University of Technology developed a robust textile antenna able to operate in harsh environmental conditions. They manufactured an antenna with different functional textile layers and they improved the performances against moisture and others environmental factors (Lilja et al., 2012).

Monarch Antenna Inc. developed a wearable antenna for soldiers using a flexible substrate worn under a vest. The antenna operates in the unlicensed ISM band of 2.4–2.48 GHz and is currently being redesigned to print on a flexible polymer substrate. Moreover, they collaborated with NASA for developing a multi-beam adaptive wearable antenna for astronauts based on Monarch's patented SSA technology (Monarch Antenna Inc., 2015).

Pharad company is a supplier of wearable antenna products. Incorporating Pharad's patented Flextenna®, they developed a flexible antenna technology for wearable applications such as a solution for first responders, soldiers, marines, and security/intelligence personnel operating covertly. Pharad offers various mounting configurations, and standard connector options allow these antennas to easily connect to most radios. The wearable antennas developed by Pharad have different bandwidths from 2–30 MHz to 3–10 GHz according to the applications (Pharad, 2015).

4.3 Conclusions

Electronic textiles describe the convergence of electronics and textiles into fabrics which are able to sense, compute, communicate, and actuate. This chapter has provided a review of the current state-of-the-art e-textiles from a manufacturing and performance assessment point of view. It has been relevant to highlight different approaches at different levels of textile integration, which show a common aim: to develop the most efficient and high performance electronic-textile structure. In relation with the method adopted to achieve fibers, yarns, or fabrics with electrical or sensing properties, the raw materials choice plays an important role. Current advances in textile technologies, new materials, nanotechnology, and miniaturized electronics are making wearable systems more feasible, nevertheless, the final key factor for user acceptance of wearable devices is the fit comfort. Overall, the desired outcome is to seek proper materials capable of interfacing with the textile structures, adding electrical/sensing features without affecting the original properties of the fabric, such as flexibility, wearability, comfort, and washability. Several issues are still present, including performance loss upon bending/stretching/washing, that still require a huge contribution from the already recalled fields, in particular, materials science and nanotechnology, to be solved.

The vision of wearable computing describes future electronic systems as an integral part of our everyday clothing serving as intelligent personal assistants. Therefore, such wearable sensors must maintain their sensing capabilities under the demands of normal wear, which can impose severe mechanical deformation of the underlying garment/substrate.

The potential applications are several and e-textile technologies have a direct link with human body monitoring. “Clothes are our own personal house” (Van Langenhove, 2007) and there are no other devices continuously in contact with the human body like garments. In this way, the combination of smart materials, wearable electronics, and sensors with fabrics opens the doors to many applications, especially in the clinical monitoring field. Textiles and clothes can be produced on fast and productive machinery at a reasonable cost, and the health and beauty industry is also taking advantage of these innovations.

Finally, the vision behind wearable computing foresees future electronic systems to be an integral part of our everyday outfits and the knowledge of circuit design, smart materials, micro electronics, and chemistry must be integrated to understand the new generation of textile fabrication.

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