# E-TEXTILES

Additional materials

# Overview

- The world of wearable devices is vast, and it is constantly expanding.
- It is intimately connected with people’s everyday lives, as anything functional to perform daily activities is actually “wearable”.
- Among all of them, wearables applied in the healthcare field are of major interest. Furthermore, the recent worldwide spread of COVID-19 is forcing several healthcare providers to rethink the way services are provided and is leading to a faster digitalization process , thus paving the way to a more intensive use of wearable devices and remote monitoring solutions in the medical field

# Overview

- By combining the notion of biosensor and wearability, a useful and comfortable technology can be obtained.
- The market offers a great variety of wearables with different characteristics and monitoring approaches.
- These are connected in what can be considered a full-fledged network, commonly referred to as body sensor network (BSN) or body area network (BAN). A complete monitoring system implies the presence of an effective communication protocol and reliable data management and processing

From the microscopic to macroscopic scale, the fabric is composed of fibres and yarns.

The former is the basic element of the textile material, whilst the latter is an intermediate material between fibre and fabrics, composed of interlocked fibres.

Both the components can be made conductive applying different techniques [18], the most used of which are shown in Figure 1


**Figure 1.** Most common manufacturing techniques of conductive textiles: knitting, weaving, embroidery; coating methods; printing methods.

**Table 1.** Synthesis of the main advantages and disadvantages of the manufacturing techniques.

| | Advantages | Disadvantages |
|---|---|---|
| Knitting | skin comfort; low weight; high elasticity | Complex manufacturing process; limitations in the choice of fabrics; damaging of the natural properties of textiles |
| Weaving | long-lasting fabrics; less likely to shrink when washing; less likely to lose colour | Complex manufacturing process; limitations in the choice of fabrics; damaging of the natural properties of textiles |
| Embroidery | possibility to lay the base material in all directions rather than in pre-defined ones (enhanced skin-electrode contact) | Complex manufacturing process; limitations in the choice of fabrics; damaging of the natural properties of textiles |
| Coating methods | good conductivity; maintenance of the original fibre properties such as density, flexibility, and handiness; resistant to corrosion. | high production cost; difficult to scale production |
| Printing methods | reduction in production cost; possibility of a large-scale production | durability of printed patterns; optimal performance achieved only with smooth and flat surfaces |

# Manufacturing of Conductive Fibres

- There are two processes to make conductive fibres: wire drawing and fibre coating. Wire drawing is a mechanical process that transforms the raw material into microfilaments with a diameter of 5–8 mm, applying forces with industrial machines. After the drawing, the microfilament is annealed at a high temperature of 600–900 ◦C to restore its mechanical and electrical properties. Afterwards, the wire is cooled and wrapped in a revolving cylinder. The most used metals for this process are copper, silver, bronze, steel, and silverplating copper.
- The obtained fibres yield several advantages. They are resistant to washing and sweat; the fibres are also strong, biologically inert, and available at low cost. Nevertheless, they are difficult to manufacture due to their heaviness [4]. Fibre coating consists of applying metals or conductive polymers on the surface of a non-metallic substrate to make it conductive [19]. The substrate can be either a fibre, a yarn, or a fabric. In the presented review, the fibre is considered as conductive unit for the purpose of clarity

**Table 2.** Materials used to manufacture e-textiles [4,20–22].

| Metal (Monofilament Fibers) | Electrical Properties | | | | | Notes |
|---|---|---|---|---|---|---|
| | Conductivity [S·m/mm$^2$] | Resistivity [Ω·mm$^2$/m] | Thermal Coefficient of Resistance [$10^{-6}$ $K^{-1}$] | | | |
| | | | Minimum | Typical | Maximum | |
| Cu | 58.5 | 0.0171 | 3900 | 3930 | 4000 | Corrosion with water |
| Cu/Ag | 58.5 | 0.0171 | 3900 | 4100 | 4300 | - |
| Ag 99% | 62.5 | 0.0160 | 3800 | 3950 | 4100 | Biocompatible, stable, rare, unaffected by moisture, resonant, moldable, malleable |
| AgCu | 57.5 | 0.0174 | 3800 | 3950 | 4100 | - |
| Bronze | 7.5 | 0.1333 | 600 | 650 | 700 | - |
| Steel 304 | 1.4 | 0.7300 | - | 1020 | - | - |
| Steel 316 | 1.3 | 0.7500 | - | 1020 | - | - |
| Conductive polymer | Conductivity [S/cm] | Doping | Limitations | | | Advantages |
| PEDOT:PSS | 4700 | P | Brittle, needs additional steps to process | | | High conductivity, resistance to humidity, stable at high temperatures, transparent |
| PANI (Polyaniline) | 112 | P | Hard to process, not biodegradable, limited solubility | | | High conductivity, stable in different environments, low cost |
| Fabrics | Category | Relative permittivity ($\varepsilon_r$) at 1 kHz | | | | Physical characteristics |
| Cotton | Natural | 3.004 | | | | Absorbent, breathable |
| Nylon (Polyamide) | Synthetic | 1.222 | | | | Breathable, elasticity |
| Polyester threads (PES) | Synthetic | 1.178 | | | | Breathable |
| Linen | Natural | 4.007 | | | | Absorbent, breathable |
| Rayon | Synthetic | 5.082 | | | | Breathable, elasticity, transparent |
| PVC textile | Synthetic | 3.118 | | | | Waterproof, non breathable |

# Manufacturing of Yarns

- As far as the yarns are concerned, these can be manufactured in different ways to form the fabrics. The manufacturing processes are knitting, weaving, and embroidering; the resulting fabric is named after the used technique.
- The processes used for smart textiles are the same as those used for regular textiles. A knitted fabric is made of a single yarn looped continuously to create a braid-shape and with the use of a needle, a series of yarns are connected.
- This manufacturing technology carries several advantages: skin comfort, low weight, and high elasticity. In fact, the knitted fabric is slightly more stretchable in width than in length, but if stretched too much it may lose its shape

- Knitted fabrics provide stretchiness and temperature control, and thus, they are preferably employed for warmth, comfort, and wrinkle resistant applications, like clothing, although they shrink when frequently washed.
- The knitting technology can be divided into weft and warp fabrics. Weft knitted fabrics, produced in flat or tubular form, are highly elastic and drapeable, while warp knitted fabrics are not much elastic while difficult to reveal

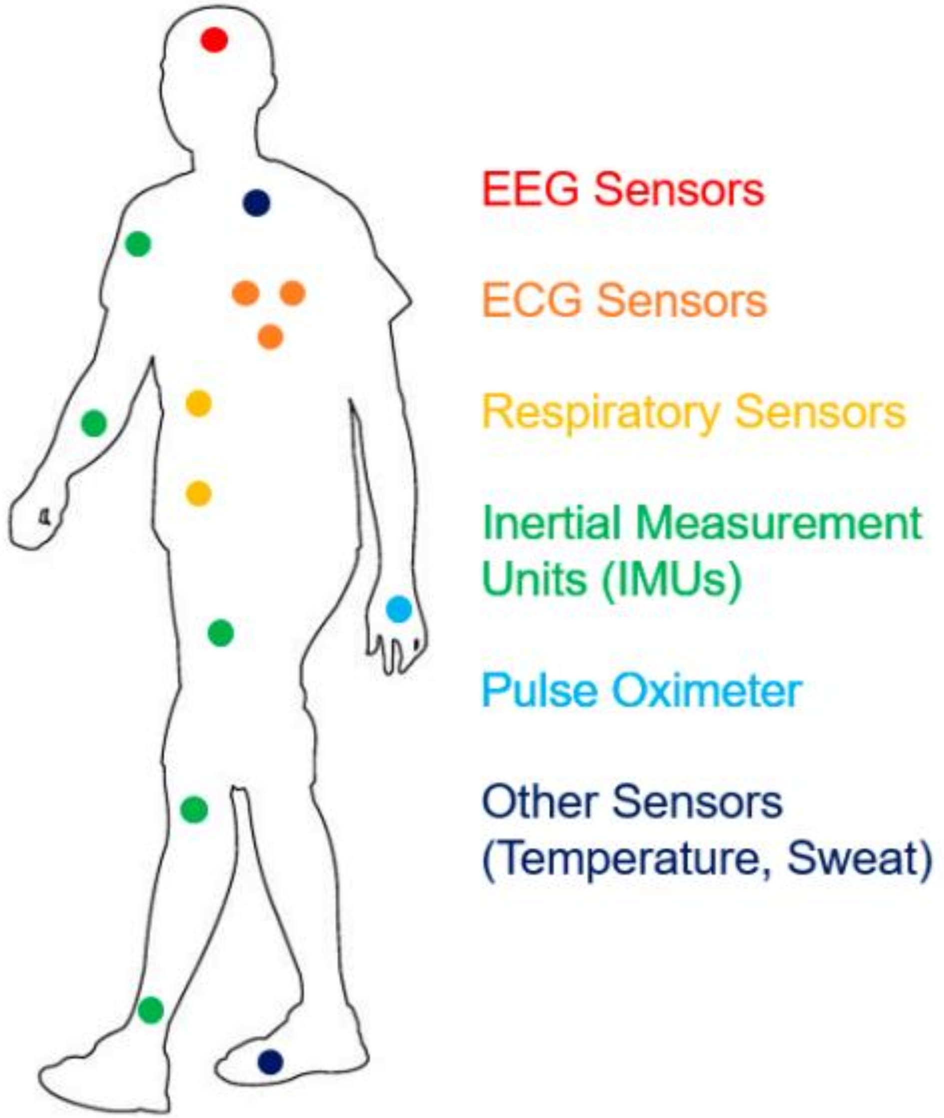


**Figure 2.** Typical placement sites of sensors that can be included in sensorized garments (ECGs, respiratory signal monitors, IMUs, pulse oximeters, other sensors).