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Review

Future Trend in Wearable Electronics in the Textile Industry

Chi-Wai Kan * and Yin-Ling Lam

Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; ylyllam@polyu.edu.hk
* Correspondence: kan.chi.wai@polyu.edu.hk

Abstract: Smart wearable textiles can sense, react, and adapt themselves to external conditions or stimuli, and they can be divided into active and passive smart wearable textiles, which can work with the human brain for cognition, reasoning, and activating capacity. Wearable technology is among the fastest growing parts of health, entertainment, and education. In the future, the development of wearable electronics will be focused on multifunctional, user-friendly, and user acceptance and comfort features and shall be based on advanced electronic textile systems.

Keywords: wearable electronics; wearable textile; e-textile; i-textile

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1. Introduction

Textiles embedded with electronic devices can be classified into three major areas, smart clothing, electrical engineering (wearable electronics), and information science (wearable computers), as shown in Figure 1 [1]. Smart clothing items integrate a high level of intelligence and can be divided into three sub-groups: passive smart textiles, active smart textiles, and very smart textiles [2,3]. Passive smart textiles are only able to sense the environment or the user, while active smart textiles can respond reactively to stimuli from the environment, which means integrating an actuator function and a sensing device, as illustrated in Figure 2 [2,4–8]. Generally speaking, wearable electronics textiles technology allows the wearer access to information in real time and has data-input capabilities [9]. Wearable textiles, a term used for very smart textiles, can sense, react, and adapt themselves to external conditions or stimuli, and they can be divided into active and passive smart wearable textiles, which can work with the human brain for cognition, reasoning, and activating capacity [1]. With features of mechanical flexibility, knittable integration, and wearable comfort, smart textiles have great potential in the context of wearable electronics [10,11]. Technological advances have enabled electronics to become smaller and more powerful to increase user mobility and comfort [12]. Many researchers have proposed their own frameworks, and Figure 3 shows the first architecture proposed by J. Nugrohu [13]. This architecture shows how wearable devices function and are connected by the human control system, i.e., Art + Fashion + Computing = Wearable Technology.

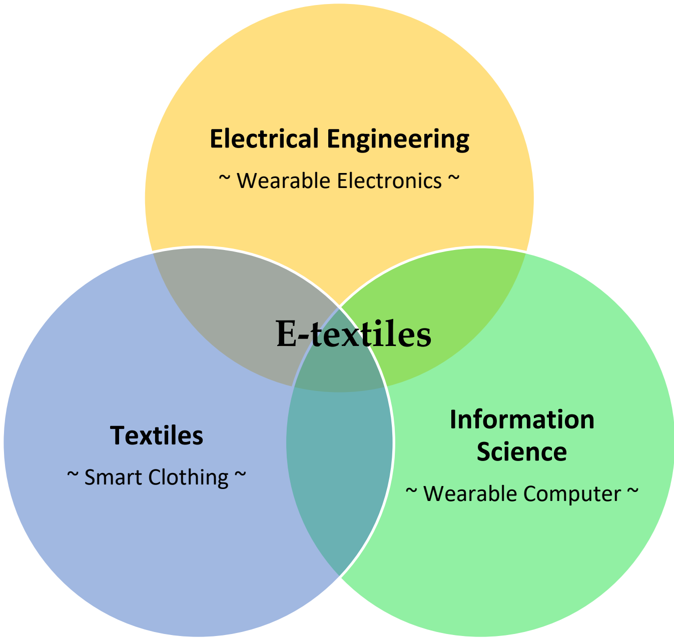

Figure 1. Area of textiles embedded with electronic devices.

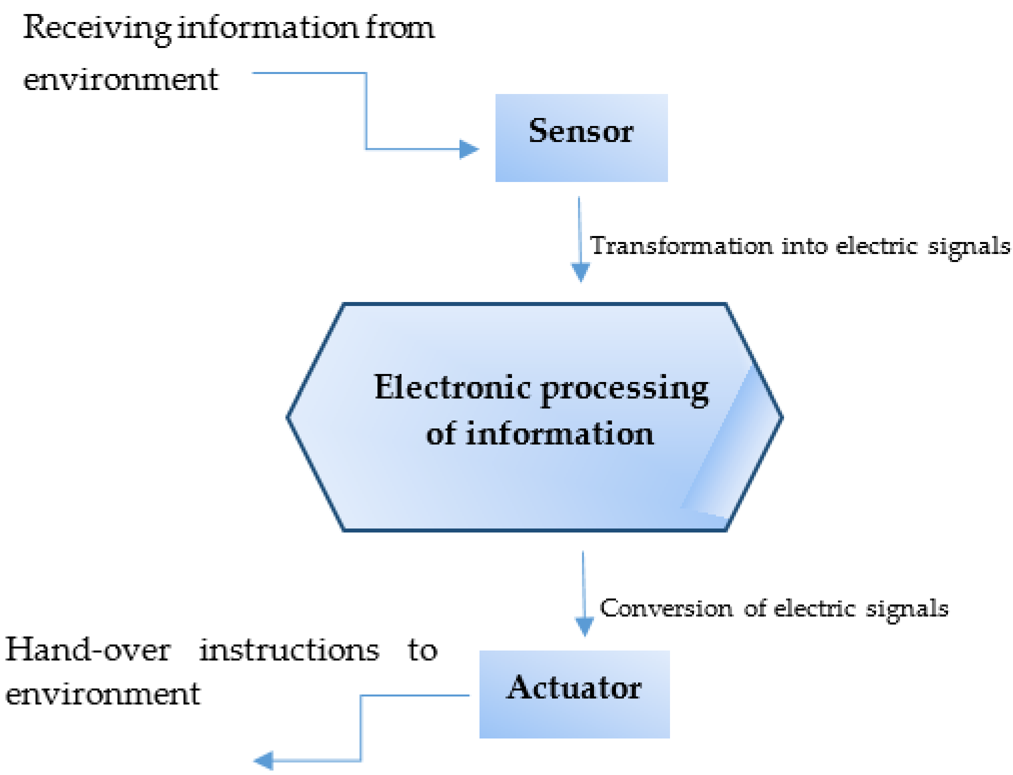

Figure 2. Principal functions of passive smart textiles.

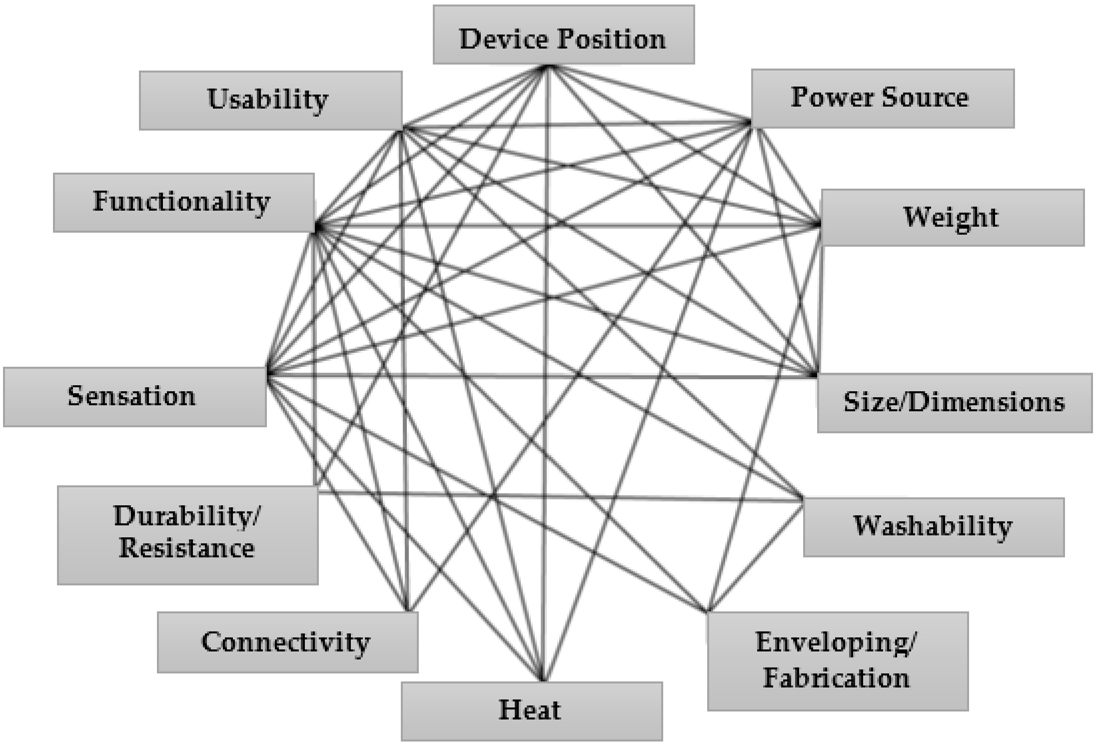

Figure 3. An interconnected architecture of wearable devices.

The architecture depicted in Figure 3 facilitates the systemization of wearable devices, as presented in Figure 4 [13]. The first level consists of a sensor, network, processor, actuator, and power unit of a wearable system, which provide different functions. At the system level, several of these functions are combined to form services such as providing information, communication, or assistance. The last level shows possible target groups for wearable electronic products [14].

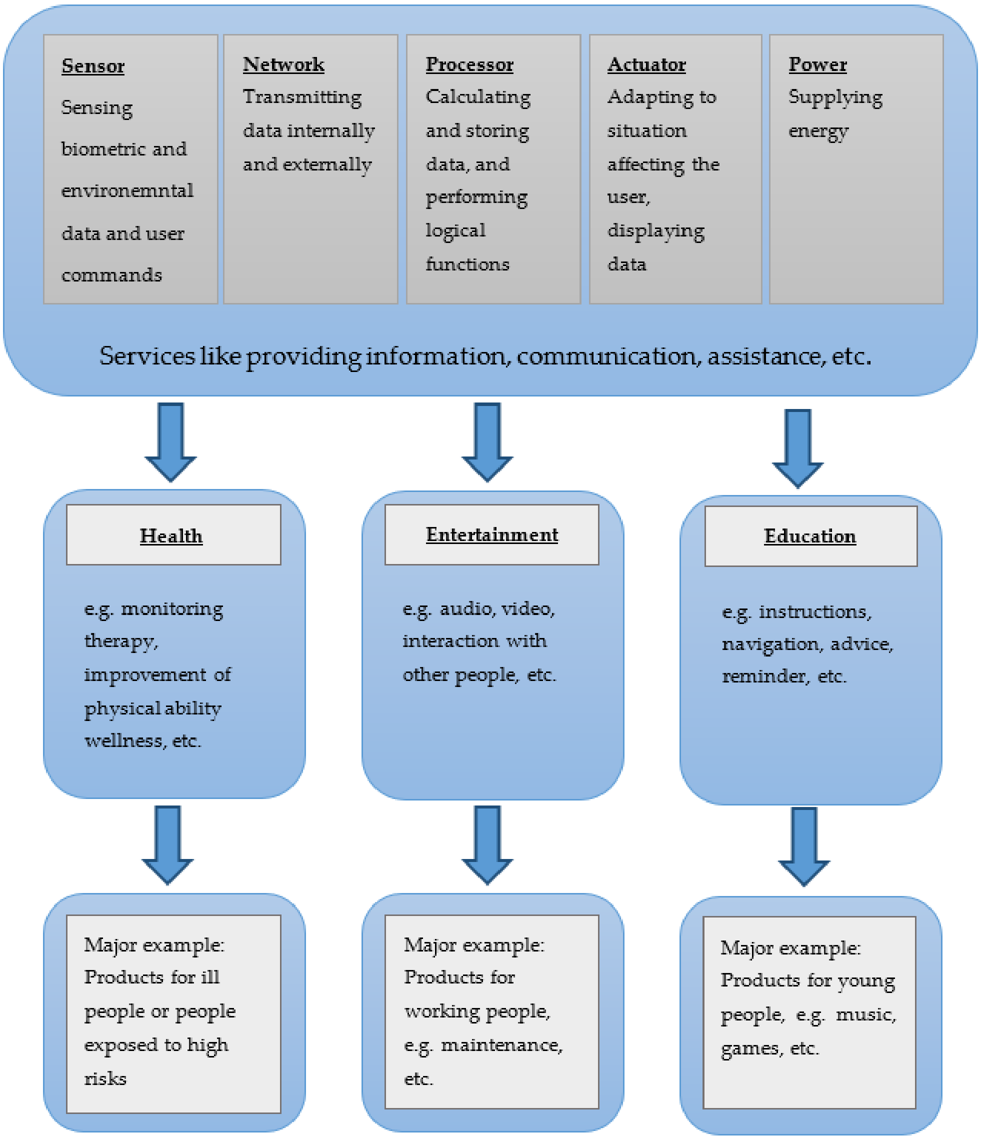

Figure 4. Systemization of wearable electronic systems.

2. Popular Applications of Wearable Technology

There are three important areas where wearable technology is growing the fastest [9,15,16], which are:

(a) *Health*

Wearable technologies for health and fitness represent some of the earliest and most popular applications [9]. Traditional medicine diagnoses, clinical interventions, and rehabilitation treatments require patients to be monitored over time. The technology is leading a slow evolution within modern healthcare. The power of wearable technology as a pragmatic and clinically useful technology to aid patient diagnosis, treatment, and care is becoming evident. This is due to its low-cost ability to gather habitual data in a discrete manner for longitudinal periods in any environment. Integration to the cloud provides readily available big data, facilitating the application of machine learning algorithms for novel outcomes [17]. Using wearable devices for the automatic monitoring of mental behavior is a feasible approach and a key marker of wellbeing for monitoring individuals with health conditions. Moreover, due to approximately 90% of our bodies typically being covered by clothing, the use of smart garments is promising. Figure 5 shows some examples of recent developments in wearable electronics for monitoring human health information [15]. Figure 5 presents the general working principles of a wearable electronic. In this example, each sensor is responsible for the specific measurement and analysis for monitoring human health information.

With the challenge of an aging population, one of the biggest drivers of market growth in this field is the need to reduce healthcare costs, in particular admissions of patients in hospitals [18]. There is a global trend in telemedicine programs, an effective way of telemonitoring patients remotely, to help address the cost of hospital admissions [19–21]. In general, human movement monitoring often needs to be associated with continuous and synchronous recording of various body signals and vital signs and electromyographic response, particularly in applications such as sports and wellness as well as medical diagnostics and rehabilitation [4,22]. Medical applications usually require measuring real-time data to quantify user ability and to provide deeper measuring capability [4]. Wearable technology started to revolutionize healthcare by assisting doctors in the operating room and providing real-time access to electronic health records [9,23].

Some of the more novel products include baby monitors and smart shirts or biometric smart wear to record heart rate, footsteps, and calories burned per day. Fabric sensors can be used for electrocardiogram, electromyography, and electroencephalography sensing; fabrics incorporating thermocouples can be used for sensing temperature; luminescent elements integrated in fabrics could be used for biophotonic sensing; shape-sensitive fabrics can sense movement and can be combined with electromyography sensing to derive muscle fitness. Carbon electrodes integrated into fabrics can be used to detect specific environmental or biomedical features such as oxygen, salinity, moisture, or contaminants [2,24–30]. These devices are becoming increasingly important in the field of medical sciences [9,19].

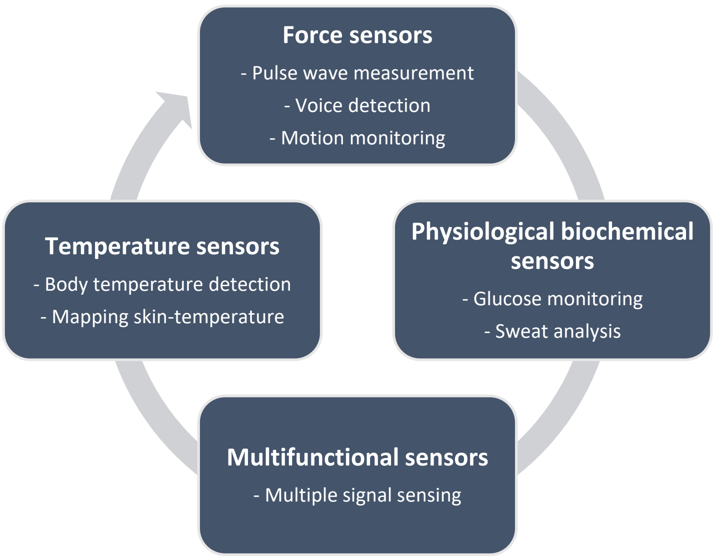

Figure 5. Recent developments in wearable electronics for monitoring human health information.

(b) Entertainment

Smart wearable devices such as miniature cameras can easily be worn on a garment while being controlled via a mobile app. These wearable devices can perform many of the computing tasks that mobile phones and laptop computers do [16]. This development is largely due to the availability of better touch screens and higher resolution cameras. Hence, this opens up another area of mobile app development wherein smart mobile apps will be created specifically to control various wearable devices [31]. Such devices have embedded software to control the device via commands received from a mobile app [9,16].

Frequently, we see small or even miniaturized cameras used to record a journey by motorbike or a bicycle tour. People wish to have a multisport tools that are easy to use, offer high-quality HD video recording, improved GPS functions, and waterproof enclosures for underwater shooting [16]. Wearable electronics allow athletes to perform their sports unencumbered while physiological (heart rate, respiration), performance (posture, movement), and environmental (temperature, humidity) data are acquired in real time, particularly in extreme sports [16,32,33]. One example is a shirt with a built-in camera allowing you to follow the soccer game from the perspective of the player. These images have allowed fans to experience the action in real speed, lowering oneself into the role of the players and experiencing their point of view [16]. Moreover, these data are important for checking athletes' health status and preventing illnesses and injuries, including cardiovascular events [33,34].

(c) Education

In education, teachers face the challenge of finding ways to acquire new wearables and how best to use them within the curriculum [9]. Some researchers believe the power of wearable devices for education is tied very closely with mobility. Similar to smart phones, wearable technology can be with the learner at all times, even when they are not physically present in a classroom or other formal training environments. Features of wearables range from data collection and monitoring of learners' behaviors and affective states, for later retrieval of experiences, to the timely delivery of personalized notifications, alerts, and reminders [35]. This makes wearable technology ideal for supporting performance in the electronic learning of content, which is delivered at the "point of need" out in the field [9].

In the education field, many wearable devices have been created to improve the teaching and learning experiences. There are several possible uses in the field of education; for example, students can document their activities in the classroom or outside the classroom; teachers can register their protocols teaching with a subjective view [16,36].

Other wearable devices are being developed that shall alert students working in chemical laboratories to hazardous conditions. Wearable cameras can allow the learner to engage simultaneously as observer and reporter while instantly capturing hundreds of photographs or data regarding an offsite trip, which can be later accessed via email or other online applications [37,38]. One of the most interesting aspects of wearable technology in education could be related to an increase in productivity. The possibility for the user to send information, with voice commands or gestures, via messages, email and social networks could help students and educators to communicate and keep track of things [4,36].

3. Electronic Textile Wearing Systems

In electronic textile wearing systems, various electronic devices such as transistors, sensors, displays, and batteries are integrated with textile substances [39,40]. Sensor-related smart textiles have high requirements because they are the critical step for perceiving the stimuli from a human or the environment, and can easily be detected from various body parts, as shown in Figure 6 [41,42]. Textile-based sensors are flexible, lightweight, and enable a good fit to multiple configuration surfaces [10]. Recently, electronic garments have integrated multiple sensors that provide physiological data such as body temperature, heart rate, skin conductivity, etc., and location data, using satellite facilities. Thus, novel flexible sensors have been developed specifically for use in smart clothing or textiles, depending on the application and end use, e.g., detection of posture and movement, biometric measurements, location monitoring, pressure sensing, and ballistic penetration and fabric damage detection (mainly in the military and safety sectors) [37].

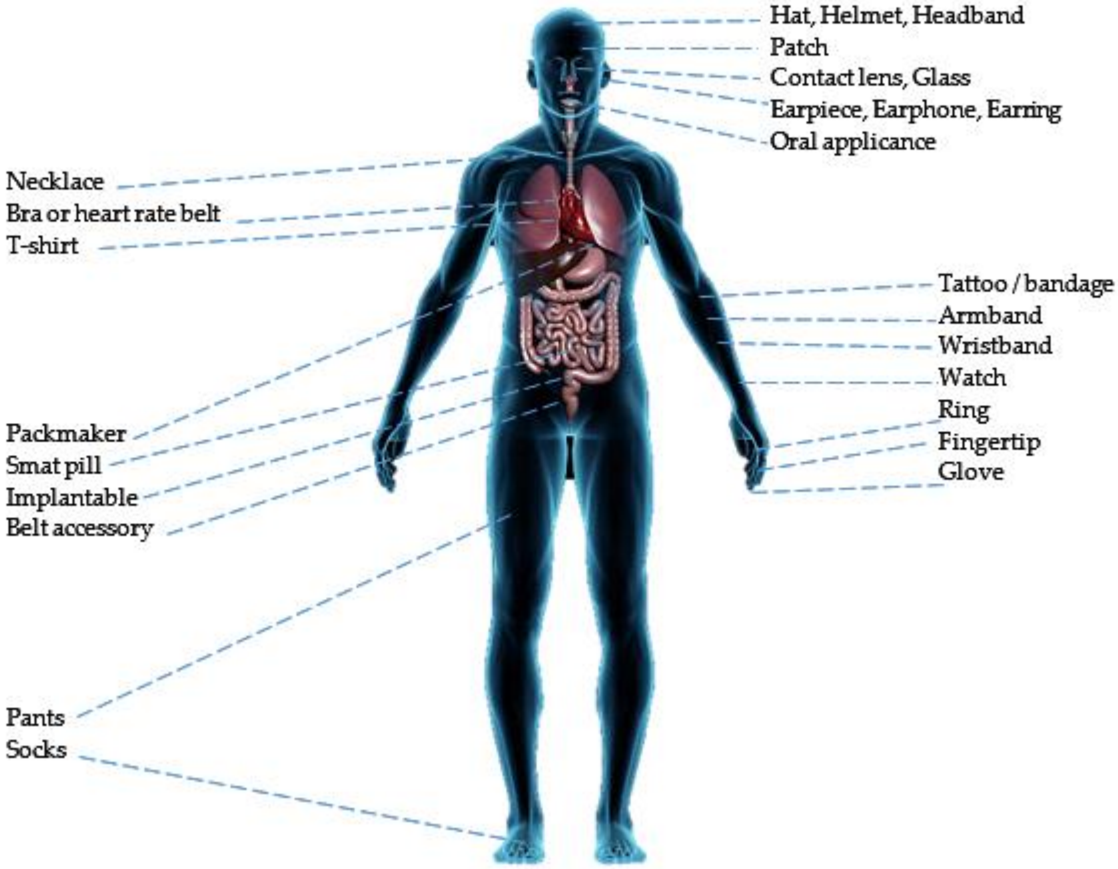

Figure 6. An overview of the different applications of wearable flexible sensors worn on various body parts.

Three levels of integration of electronic components and circuits can be distinguished in currently available products, which are textile-adapted, textile-integrated, and textile-based (Figure 7). The first level, textile adaption, refers to the manufacturing of special clothing accessories to put in electronic devices such as MP3 players. In the second level, the integration of electronic components means creating an interconnection between electronic elements and the textile within (e.g., metal push-buttons), for possible removal. The last level of integration of electronic components is based on the textile structure itself, such as with electro-conductive or metallic-coated multi-filament yarns [8].

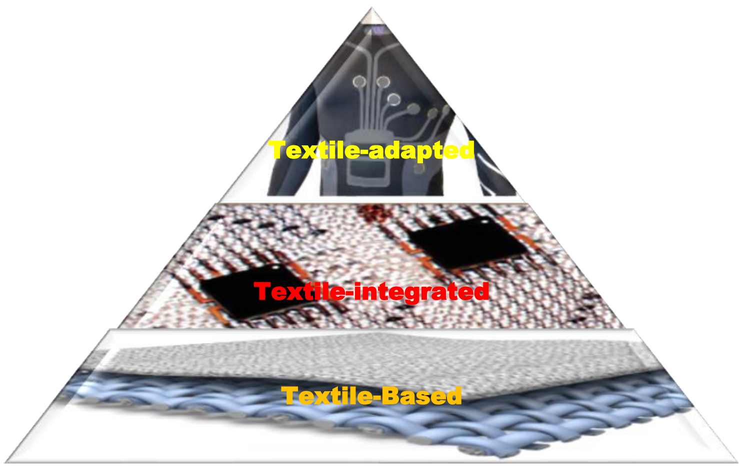

Figure 7. Levels of integration of electronic components.

4. Technical Limitations in Wearable Technology

However, more work is still needed to resolve all technical limitations, particularly with regard to the following: (a) accuracy and reliability of data measurement (noise reduction); (b) reliability, safety, and security of data transfer; (c) minimization of the number of additional attachments (simplification of the system by multifunctional textiles); (d) efficiency of power management, including power generation; (e) durability of the systems, including washability and long-term accuracy in performance; (f) user-friendliness, including the ability to use/wear the garments without assistance; (g) mobility, including weight reduction; (h) cost versus product lifespan or durability; (i) comfort and physical aesthetics, including breathability, absorbency, drape, handle, etc.; and (j) health and safety [43].

(a) Accuracy and reliability of data measurement

The market for smart textiles still lacks maturity. Current systems need improvements in terms of reliability, such as accuracy, repeatability, and reproducibility [44]. Responses are needed regarding the risk of interference of wearable electronics with communication systems and other electronic systems such as pacemakers. Moreover, internal and external environmental conditions such as profuse sweating or rain may also interfere with smart textiles proper operation [44–46]. Conventional rigid-type sensor devices, which show high electrical performance, can be easily manufactured by conventional processes. Nevertheless, it is difficult to obtain accurate physiological signals because it is not easy to make strong contact with the human body. A research showed that the Near Field Communication (NFC) antenna is seamlessly integrated with closed-body garments, and the sensor data can be easily acquired by NFC readers and smart phones in order to achieve real-time and wireless monitoring of health status in a convenient and nonintrusive way [46]. Both temperature and sweat sensors powered wirelessly by the reader are able to provide accurate and reliable results. It is believed that the wireless powered smart textile sensing system reported possesses potential to be widely applied into daily health care system and wellbeing monitoring, but more research and developments still needed. There is even a problem that electrical performance is weakened because of deformation on bending, stretching, or twisting [47]. In addition, there are still challenges of newly developed sensors, e.g., carbon-based materials, in terms of compact design, low-cost fabrication, device protection layers, multifunctional sensing, and integration techniques for realizing fully embedded practical wearable electronics.

Relevant knowledge, standards, and test methods are also important for understanding of a new product's operation and the generation of data about device safety and behavior over time. The lack of appropriate standardized test methods and regulatory framework may generate risks for the user [44]. For medical devices, safety and security are primary considerations, tightly coupled with reliability at all system levels. Increasing importance is being assigned to these major user concerns. If a wearable device is required to perform critical functions safely, the tolerance for error is zero. A failure in such a device can cost a life, and that requires more effort, cost, and time to be invested in thoroughly testing and validating the device before it is deemed safe to use [48].

(b) Reliability, safety, and security of data transfer

Communication systems in electronic textiles, such as Bluetooth, allow for connectivity of the textile to other intelligent devices for the visualization and analysis of data obtained in real time [49]. In this context, the vision of smart clothes promises greater user-friendliness, user empowerment, and more efficient services support [50]. In addition, the most addressed concerns from the user perspective are technology acceptance and issues related to safety and security, implying privacy and reliability as important topics for further study [44,48]. For example, data collected by wearable devices include geolocation and other sensitive user information, and such devices have the capabilities to capture and transmit information about the surroundings, e.g., via speakers [51]. Therefore, ensuring the security and privacy of information collected by such technologies is crucial because information privacy is the right of an individual to exercise control over the collection, use, disclosure, and retention of his or her personal information. It is challenging to convince the actual users to adopt wearable electronics, especially in healthcare environments because of the need for protection of privacy [52].

(c) *Minimization of the number of additional attachments*

Existing electronics manufacturing requires a stiff substrate on which components are soldered in the traditional way. However, a dramatic restructuring of the tools and processes used in apparel and textile assembly is needed for electronic textiles advancements [53]. New technology allows the integration of sensors and stimulating devices in the textiles without rigid components. However, given the variety of textiles available in the market, no single recipe fits all needs. Depending on the texture of the fabric, pre- and post-treatments are necessary to put down electrical circuits on the fabric [54,55]. In general, each smart clothes system contains hardware and software parts, including control, sensing, actuator, communication, location, power, storage, display as well as the interconnection and software subsystem. These systems utilise various sensor units, including detection of motion, gestures, position sensors, temperature sensor, and location sensor [3,56,57]. Then, minimization of the number of additional attachments to the wearable electronics is critical.

(d) *Efficiency of power management*

The increasing attention being paid to wearable energy storage devices is triggered by the growing demand for wearable electronics, where besides the energy/power density, lightweight and comfort are also essential requirements. An ideal power device for smart textiles should be in the form of a textile, which can be readily incorporated into a garment without much sacrifice on softness, lightweight, or comfort [58]. In recent research, it was found that printable techniques show promise for the fabrication of power supply devices with practical scalability and versatility, especially for applications in wearable and portable electronics [59].

A recent study has demonstrated the feasibility of all-inkjet-printed graphene on a rough and porous textile surfaces for wearable electronic applications. Due to the rough and porous textile surface, it is challenging to produce a continuous conductive track onto textiles by using low viscosity graphene-based inkjet printable inks. Therefore, the study proposes an organic nanoparticle-based surface pre-treatment on textiles that reduces the sheet resistance of graphene-based conductive prints [60]. One of the challenges with current reduced graphene-based electronic textiles is that they suffer from poor electrical conductivity and higher power consumption.

(e) *Durability of the systems*

Smart textiles are subjected to severe bending, twisting, and stretching during usage. Therefore, the mechanical properties and washing behavior of the wearable electronics need to be good, but until now, the available wearable electronics are poor in cyclic stability and long-term durability [41,54]. In the case of monitoring systems that encounter harsh environmental conditions or movement (e.g., for use in sports activities, fire-fighting exercises, military conditions, or extreme environmental conditions), the robustness of the system is an essential criterion [43]. One of the critical challenges about wearable electronics is to make them reusable and efficient enough and to overcome the washing process [5,61–64]. Textile-based sensors are prone to damage during washing, heat cycling over time, and exposure to dust and sweat. It is significant to seek an economical method to produce highly conductive and durable conductive sensors with superior sensitivity and durability that can work well in harsh conditions, i.e., at high humidity and high temperature. Such performance will be critical to the commercial success of wearable textiles, since products designed for only a single use are expensive [5,41,65–67].

(f) *User-friendliness*

Wearable electronics are mounted on textiles, and thus, the washability of them is important. Usually, the textiles are washable only when all electronic components are removed. Therefore, developing a waterproof enclosure for electronic components will surely be an important issue to address [3]. Indeed, it is important that electrically conducting fibers should be easily connected to other components. For being user-friendly, they should be able to resist the common cleaning procedures, i.e., be machine washable and robust to tumble drying. They should resist damage through fatigue, and the fibers should also be dyeable. The system should be intuitive, easy to learn, without the need for extensive and expensive training, and easy to use or wear without assistance. All these requirements could be considered in long-term aims of wearable electronics development [8].

(g) Mobility

A major limitation to smart textile use is related to batteries: their weight and bulkiness as well as the charging process [44]. In the commercial market, there are already many wearable non-textile products, for instance, smartwatches and wrist bands, which are used to monitor activity and the wearer's health parameters. However, electronic devices integrated into textiles can offer several advantages, such as enhanced mobility and comfort, and for the user, these can offer effective solutions for wearers who seek more detailed data about their fitness and performance [68,69]. Smart textiles can also eliminate the use of bulky equipment such as chest straps. Since athletes and major league players constantly strive to improve performance, an opportunity for storing data for analysis by lightweight devices that can be embedded in their sportswear offers a high potential for further performance enhancement [70].

(h) Cost versus product lifespan or durability

In particular, mass production and low-cost materials with superior performances are needed. In addition to cost issues, it is necessary to further develop a higher sensitivity and longer operational stability of sensor devices in order to realize practical applications that can precisely detect human activities or physiological signals [47]. The development of military uniforms, integration of sensors and actuators can increase functionality, e.g., developments in communication devices. There are three main areas in such devices, which are personal communication networks, wide area networks, and information systems, as shown in Figure 8 [8]. Nevertheless, the incorporation of sensors, actuators, and other electronic components into military uniforms increases the overall cost of the final products, depending on the number and types of additional functionalities incorporated into the clothing. As the application of electronic textiles in military usage is still in an early stage, the initial cost involved in the design and development may be high. The cost should decline when the technologies become mature and electronic textiles become bulk military items. Furthermore, the increase in cost could become less significant when various life-saving features are added to military clothing [8].

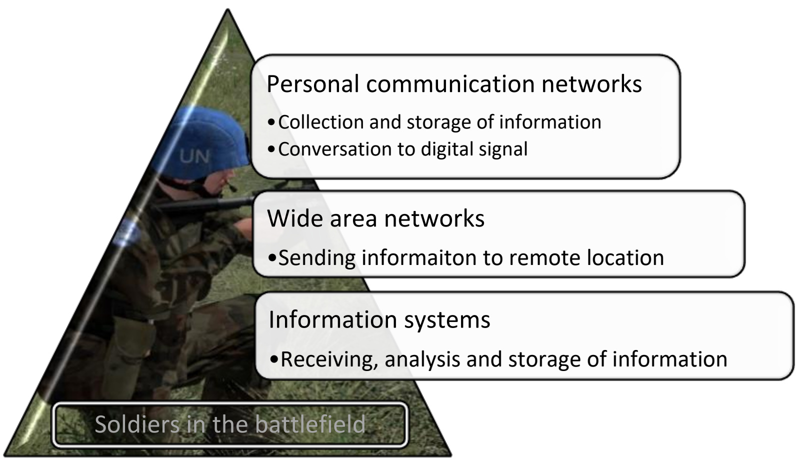

Figure 8. Three areas of communication devices for military applications.

(i) Comfort and physical aesthetics

Knitted fabrics are more flexible than woven fabrics, and therefore, when stretchiness and flexibility are needed, knitted fabric structure is an option. On the other hand, when a rigid structure is required, woven fabrics are a better choice. The direct insertion of conductive yarns into the weaving and knitting manufacturing processes, sewing, or embroidery systems are possible manufacturing routes for electronic textiles. Embroidery is defined as a decorative arrangement of yarns, cords, and/or beads on the fabric to obtain the desired configuration on the surface [5,71]. Digital embroidery designs allow combining electronic components on textile surface, i.e., conductive yarns can be embroidered with or without the conventional yarns to create an electrical conductivity feature on the textiles to let the current pass through the embroidered design [5,72]. Coating, printing, and the deposition of electroconductive solutions on knitted, woven, and nonwoven fabric surfaces are also alternative ways for the manufacturing of electronic textiles [5]. However, most of the applications are still in prototype form, and the mass fabrication of electronic textiles is still a challenge [5,39].

(j) Health and safety

Concerns have been raised about particles of all sizes entering or generated during the manufacturing process, as well as during use. This includes the potential toxicity of nanoparticles and metals, effects of electromagnetic fields, accidental electric shock, and the inability to activate the emergency shut-off device in case of malfunctioning of smart protective textiles [44]. In addition, smart textiles present the same challenges as traditional electronic waste. Smart textile wastes contain problematic as well as valuable substances and are often disposed along with their batteries. In particular, it is critical to ensure that the waste generated by use of smart textiles does not create new hazards for health and the environment [44].

5. Important Features in Wearable Technology Development

Based on the challenges discussed above, there are some important features that should be considered in future studies of wearable electronics:

(1) Multifunctionality

In the future, wearable electronics shall have to integrate the detection of multiple signals such as strain, pressure, temperature, humidity, gas, and so on into a single device to provide more comprehensive information [15]. In the future, capabilities for human motion detection, personal healthcare monitoring, intelligent robotics, and thermal regulation and integrated wearable sensing systems that can simultaneously detect multiple health-related signs shall be needed [73]. A number of sensors may be used to measure attributes such as motion, location, temperature, and electrocardiogram. Sensor data are collected, and after analysis of acquired data, these data are made available to the patients, caretakers, wearers, or healthcare professionals [74]. Smart systems that can interact with human body are even more attractive. Depending on the response time, these approaches may be either offline or online. The hierarchy of these two approaches is shown in Figure 9 [74,75]. Online approaches immediately recognize the action performed and give feedback accordingly. On the other hand, offline schemes require more time to respond to the actions performed, and they demand high computation and are suitable for applications that do not need immediate feedback in real time [74,75].

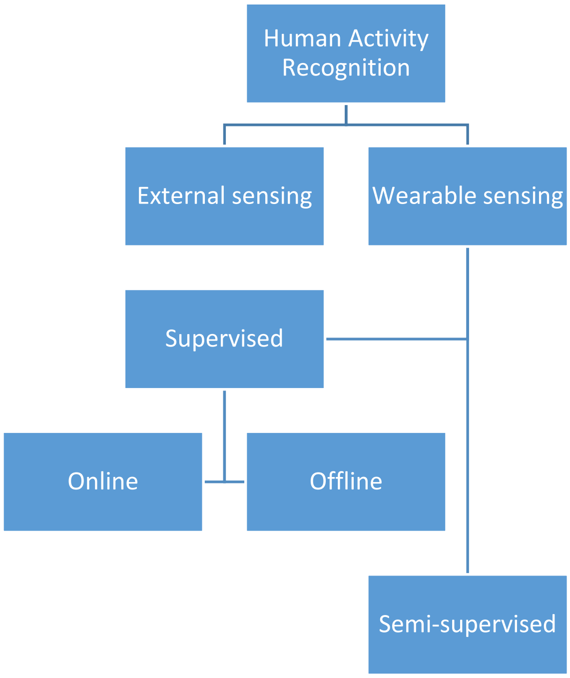

Figure 9. Approaches of human activity monitoring.

In spite of several existing challenges, many researchers are focused on merging at least two categories of sensors into a flexible device. Particularly, the integration of temperature and pressure/strain sensors has attracted massive attention [76]. Pressure and strain sensors are responsible for sensing vibration, pressure, and other mechanical stimuli and are viewed as the key components of electronic skin. Although significant advancements have been achieved in the fabrication of pressure sensors and strain sensors with high performance, one critical challenge commonly recognized in this field is how to make these devices satisfy the requirements of personal comfort [73].

(2) *User-friendly and user acceptance*

The interaction of individual humans with electronic devices demands specific user skills. In the future, improved user interfaces can largely solve this problem and push the usage of micro-electronics considerably. In this context, the vision of smart clothes promises greater user-friendliness, user empowerment, and more efficient services support [50]. In addition, the most addressed concerns from the user perspective are technology acceptance and issues related to safety and security, implying that privacy and reliability are important topics for further study [48]. The safety concerns of electronic textiles include the following: (i) Electrical components of electronic textiles are mostly nanomaterials, which usually require a comprehensive assessment of their effect on the human body and environment. (ii) For energy conversion and storage, electrolytes are often introduced in electronic textile systems that can cause harm to the wearers if the electrolytes leak. (iii) The possibility of electrical leakage should be considered, since the salient sweat can erode the protective coating layer and let the skin come in direct contact with electrical components of the electronic textile. (iv) The ohmic heating during the operation of electronic textiles can cause scalding of the skin, especially in case of infants. (v) Some fiber-shaped electronic devices such as batteries often require the use of flammable and toxic organic electrolytes, and they entail risks of fire and explosion induced by short-circuit during deformation. (vi) Lastly, dyes used in traditional textile industry, which cause severe water and air pollution, can lead to environmental problems in case of electronic textiles also [77,78]. All these issues should be considered and minimized in the mass production and application of electronic textiles.

Wearable devices with embedded sensors can collect, process, and transfer the information of the users. Therefore, as market penetration expands, wearable sensors are expected to generate huge volumes of personal data, where the leaking of sensitive information can have deleterious effects [76]. More and more researchers are focused on resolving the security and privacy concerns in the context of wearable technologies. The leakage of personal information may lead to fraud and a series of social problems. Future work should focus on not only developing systems with adequate security but also exploring efficient security mechanisms to protect data of wearable devices from social engineering attacks [77,78].

(3) Comfortability

To successfully develop a sustainable and independent wearable multifunctional system, a power module capable of facilitating efficient signal generation, transmission, and processing is absolutely necessary [76]. For textile supercapacitors, one of the major difficulties lies in the realization of conductive electrodes on wavy woven fabrics. Metal wires or meshes have been widely used as electrodes for wearable energy devices; however, the heavy weight and stiffness of the metal wires or meshes make the textile uncomfortable [79]. Nevertheless, for wearable applications, flexible and stretchable electronic devices are very appealing. So, it is of great significance to exploit new functional wires or fibers with good mechanical and electrical properties as well as fine wearability, especially soft hand feeling [80].

The development of flexible batteries is also an essential strategy to conform to the mainstream of wearable electronics. However, such flexible energy-storage devices are limited by relatively low energy and power densities, hindering their practical applications, especially in remote regions. Self-powered systems, which can transform the ubiquitous energy from the ambient or human bodies, are new techniques expected to substitute the traditional bulky power components. The system primarily includes mechanical energy, thermal energy, as well as solar energy [70].

Moreover, some researchers have reported that the electroless deposition of thin Ni film on polyester fibers can constitute electrodes that combine lightweight, flexibility of polymer fibers, and high conductivity of the metal film. Some carbon- and graphene-based nanomaterials are also being created and used in sensors because of properties such as flexibility, portability, and wearability [56,80–87]. The graphene-based electronic textiles even show high stability to repeated home laundering [81]. Moreover, a laser-scribing masking route to fabricate conductive textiles with any intended pattern or drawing has been developed [58]. Some more advanced techniques such as printing and roll-to-roll processing should be well explored for cost-effective, large-scale and mass manufacturing of flexible electronics, e.g., carbon-based, to ensure commercialization and practical applications [76,88–90]. Inkjet printing is one of the manufacturing technologies for depositing a conductive layer on various substrates, which provides high resolution, design freedom, and green production for fabric-based electronic applications [90–93].

(4) Advanced electronic textile system

Next-generation electronic textile systems can be envisioned as completely integrated fiber-based electronic textile devices with enhanced optoelectrical and mechanical properties that consume the minimal power or have self-sustainable device features. In addition, the development of bio-safe and less irritating materials should not be overlooked for long-term continuous operations near or on human body [39]. The term interactive textiles is newly proposed to convey the dynamic or interactive nature of fabric structures that go beyond just the integration of electronic elements into textile structures. The fabric eventually becomes a computer, and such wearer–garment symbiosis and dynamics open up new frontiers in textiles and human-factor research [94]. The performance requirements for interactive textiles (Table 1) have been achieved through the proper selection of materials and manufacturing technologies [94].

Table 1. Performance requirements for interactive textiles.

Functionality - Act as a flexible motherboard - Domain-specific sensing, monitoring, and processing capabilities (dictated by the intended end use)	**Usability** - Protecting an individual's personal information - Security in data transmission and usage - Electrostatic charge decay - Resistance to electromagnetic interference - Hazard protection - Flame resistance and directed energy retardance - Thermal protection	**Durability** - High flexural endurance - High mechanical strength - Abrasion resistance - Corrosion resistance - Heat resistance - Electrical resistance
Shape Conformability - Ability to conform to the desired product shape - Dimensional/shape stability during repeated use		**Maintainability** - Ease of care - Ease of mending - Ease of diagnosing problems - Launderability
Connectivity - Ease of integration with sensors, processors (computing, wireless communication), monitors, and other equipment - Ease of connection to power source (battery charging and replacement) - Ease of connection to other interactive textile modules	**Affordability** - Cost of materials, manufacturing, and maintenance	**Manufacturability** - Ease of fabrication - Compatibility with standard manufacturing machinery

Furthermore, one researcher has reported that a light, sustainable, and flexible power source has been developed by constructing a wearable power textile using a simultaneously electrospinning and electrospray approach. The power generation fabrics can get deformed easily in any direction and when rationally integrated into the personal clothes, exhibit great effectiveness for scavenging energy from human walking or running. More importantly, these textile fabrics can monitor human movements and postures and can be used as highly sensitive human motion sensors. This will be a new direction in next-generation wearable products [95].

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