COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Applications of Smart Clothing – Brief Overview

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ABSTRACT

Smart clothing is the next evolutionary step in wearable devices. It integrates electronics and textiles to create functional, stylish and comfortable solutions for people's daily needs. The concept includes not only clothing, which is a covering mechanism for the body, but also has the function of tracking body indicators in certain situations. This review introduces the classification and concept of smart clothing and the application areas such as sports, workwear, healthcare, military and fashion. It will also outline the current state of smart clothing and the latest developments in the field, and discuss future developments and challenges.

1 Introduction

Nowadays, technical possibilities are growing in a wide range of areas. Therefore, people are getting more sophisticated and start to search for the most convenient and technologically equipped items in daily life. With the development of intelligent technologies in the traditional manufacturing industry, a wave of intelligent clothing is in trend, where electronic parts are incorporated into textiles and clothing to make life easier [1]. The companies such as KYMIRA®, Thread in Motion, Prevayl Limited, and Myontec are introducing technological amenities and advanced electronic devices into clothing [2-5]. These companies focus on smart clothing and textile technology that integrate flexible electronic systems into practical and comfortable garments for remote diagnosis and remote monitoring in healthcare and professional sports and allow wearable biosensor monitoring solutions. A huge advancement for the clothing industry has been the introduction of technology that can not only perform its function of protecting and covering the human body, but also collect and process data about the condition of the body and its reactions to various situations [6-9]. Nakashima *et al*. developed a new body-worn bioelectrode that continuously measures electrocardiogram and heart rate while the clothing is worn [10]. Li et al. reported about the semiconductor technology of a wearable device, which is used to predict health analysis [11]. In addition, this technology enables the detection of physical performance and physiological conditions in order to reduce the risk of injury and enhance performance [11-12]. The feedback process, which shows reactions of the body, can help to restructure and adjust certain patterns of human action and behavior. It allows seeing lifestyle habits by collecting accurate data over long periods of time [13].

This brief overview presents the state of development of smart clothing and discusses applications in sports, workwear, healthcare, military and fashion fields, analyzing and explaining future trends and challenges. The focus of this study is based on recent and experimental studies and review publications.

2 Brief definition

Integration of electronics in textiles can be divided into three classes such as smart clothing, wearable electronics and wearable computers [14,15] (cf. Fig. 1).

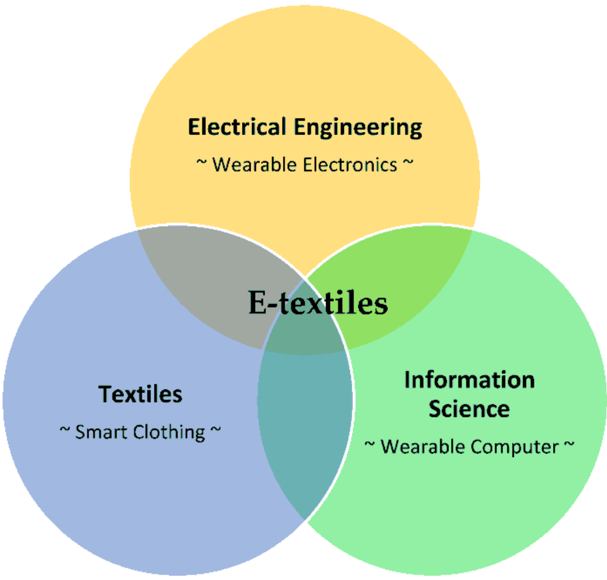

Fig. 1 Area of textiles equipped with electronic devices. Reproduced from reference [14], originally published under a CC-BY 4.0 licence.

Smart clothing combines the latest technology with traditional textile and clothing design and technology [16]. The integration of the latest technological achievements in smart textiles and smart clothing is entering many industrial fields such as medicine, fashion, sports and fitness, military and security [17-20]. The interpenetration of multidisciplinary technologies, the rapid development of new technologies as well as industrial digital upgrading promote the entire textile and garment industry to carry out rapid technology-intensive transformation [21].

The idea of developing smart clothing and integrating them into our daily lives requires a high demand for smart products, which can be used in various areas of life (Fig. 2), such as medical fields, implants, medical aids, elderly care, work and sports, workwear, military applications, astronautics and space, communication etc. [22-26]. In particular, there is a high demand for smart clothing in fields such as medicine, nursing and healthcare, military and fire protection [27]. Moreover, the Covid-19 pandemic is forcing medical organizations to rethink the way they provide services and is leading to an acceleration of more intensive use of electronic technical devices for remote medical monitoring [28].

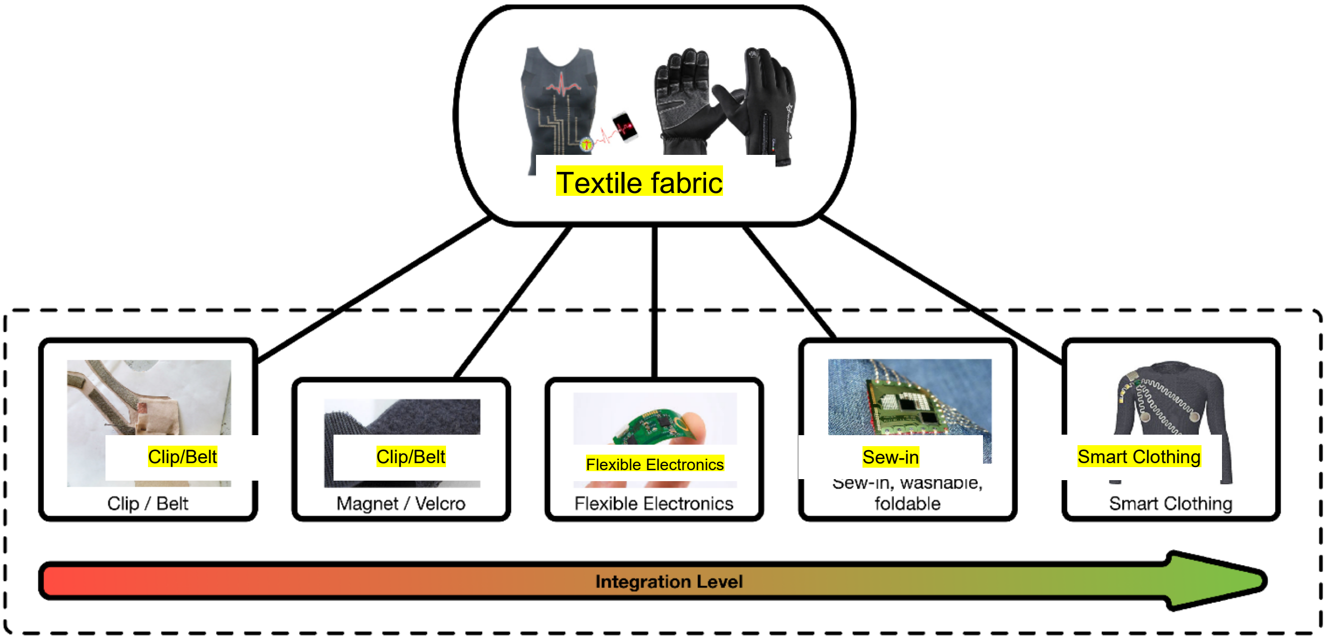

Fig. 2 Integration levels of smart clothing. Adapted from reference [25], originally published under a CC-BY 4.0 licence.

3 Market development

The smart clothing sector evolved in the last two decades from research explorations into a significant manufacturing field. It started in the 1990s with investigations of searching the ways of integration conductive lines into textiles to the integration of sensors, user interfaces and complex textile circuits. Therefore, a completely new application field was created and existing applications which are centered around sensor-based monitoring and interactions were refined [26].

The market for smart wearables is at the moment very small, with expected sales of 387 million euros in Germany in 2020 (0.6% of the total German apparel market). However, this figure is expected to rise to 703 million euros in 2022. And this trend is also evident globally. The global market volume of “smart textiles” is expected to reach around 4.7 billion euros in 2022 [27]. The global smart fabrics market is estimated at US$ 3.6 billion and will rise to reach US$ 11.4 billion by 2027 [28].

Sensor-based monitoring applications include acquiring vital signs in medical monitoring, estimating physical activity in sport, and safety systems for soldiers or firefighters [29]. Medicine, which is the main driver of the market for electronic textiles, is the fastest-growing market at the moment. The decade 2015-2025 has been recognized as the “era of wearables”, and the market is expected to exceed US$ 5.55 billion in the next five years [30]. According to rising sales figures, smart garments will change the way we interact with computer systems in the future. So, the combination of the ubiquity of clothes and the interaction could be continuous and can regard the complete body. In the current situation, interaction techniques are usually realized with user input through touch or voice systems, but soon smart clothing can respond to sensitive body contact with fingertips, leading to more developments in this area, more jobs and revenue in the field of smart textiles and smart clothing.

4 Intelligence levels of smart clothing and materials

Smart clothing can be defined as a clever or intelligent kind of clothing [31]. In the literature, there is no clear definition of intelligent clothing and it can be classified according to so-called intelligence levels [32]. For example, textiles can have additional smart benefits such as stain-resistant, non-ironing or odor-blocking properties. Another intelligence level involves materials that can change physical states or properties. The other stage is represented by garments that can be equipped with integrated electronic microsystems. The next level can be described as clothing that has a directly integrated electronic device. The last level is all clothing which has an integrated electronic system that also has smart functions. For example, a music player mutes itself when the mobile phone rings. Also the term "wearable'' plays a role in smart clothing, which simply describes the form of wearable computers [32]. Normally the term is used to describe electronic devices which are so small and lightweight that they are wearable [33-34].

Some textiles keep bacteria out and keep surfaces clean, sometimes not just from dirt, but also from coffee and wine stains, or eliminate unpleasant odors. Ye et al. report about double-nano-particle configured textile coatings that impart superhydrophobic and antibacterial properties to textiles [35]. Qin describes the use of activated carbon for odor control in medical textiles [36]. A self-cleaning coating is called hydrophobic when water droplets roll off the surface and thus cannot penetrate into the fabric. Anjum et al. reported about structured nano-silica from coral reefs with self-cleaning and superhydrophobic textile properties [30]. Moreover, this coating exhibited excellent antifouling and antifungal performance [37]. The use of nanotechnology in combination with inspirations from nature such as the lotus leaf effect results in efficient self-cleaning concepts for textiles. The fabrication of self-cleaning textile surfaces can be realized by the use of microwaves, the use of carbon nanotubes, photocatalyst coatings such as TiO_2 and other advanced materials, as reported in the review by Afroz et al. [38]. In the study by Çakır et al., textiles were coated with copolymer solution containing ZnO nanoparticles and demonstrated relatively high photocatalytic efficiency and excellent UV-blocking, self-cleaning and antibacterial properties against *E. coli* and *S. aureus* [39]. The use of photocatalysts, which consist of a thin layer of a mixture of titanium dioxide and zinc oxide particles, makes it possible to break down dirt into carbon dioxide and oxygen when exposed to light. As a result, the surface remains clean [40]. Phase change materials (PCMs) can change their physical properties [41-42]. Thermal energy storage using microencapsulated phase change materials to improve the energy efficiency of buildings was reported by Bahrar et al. [42].

Scientists have made it possible to build processors and sensors into small electronic devices. Sensors are added to improve the convenience of these tools and improve the quality of the experience by collecting and processing information [43]. For example, a piezoresistive smart textile sensor for inventory management was developed by Hossain et al. which can detect the items based on their weight and relay the information wirelessly to a control center [43]. The data may be useful for device users to enhance the operation, manageability, and progress of such components. Another example of a highly elastic capacitive pressure sensor based on smart textiles was developed by Vu and Kim for monitoring human movements. This multi-purpose capacitive pressure textile sensor can be used for wearable electronics and especially in healthcare and sports where human movements are significant. The sensor consists of single-wall carbon nanotubes (SWNCTs), silver paste, encapsulation pastes and is based on a polyester/spandex (PET/SP) spacer fabric [44]. Meding et al. reported on the development and comparison of electrodes which were made of cotton fabric as well as a silver-coated yarn and partially conductive poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) Orgacon ICP 1050 with dip coating and a Powersil coating. This electrode is of interest for the medical field of angiopathy as well as for bioimpedance measurements in compression therapies [45]. Jing et al. developed a flexible carbon-based thin-film actuator with a 1D-to-2D transition structure, which can be used in smart clothing, soft robots and wearable devices [46]. The portable, grounded, flat loop antenna with a high impedance surface structure (HIS), shown in Fig. 3, was developed by Bait-Suwailam et al. for a medical application [47].

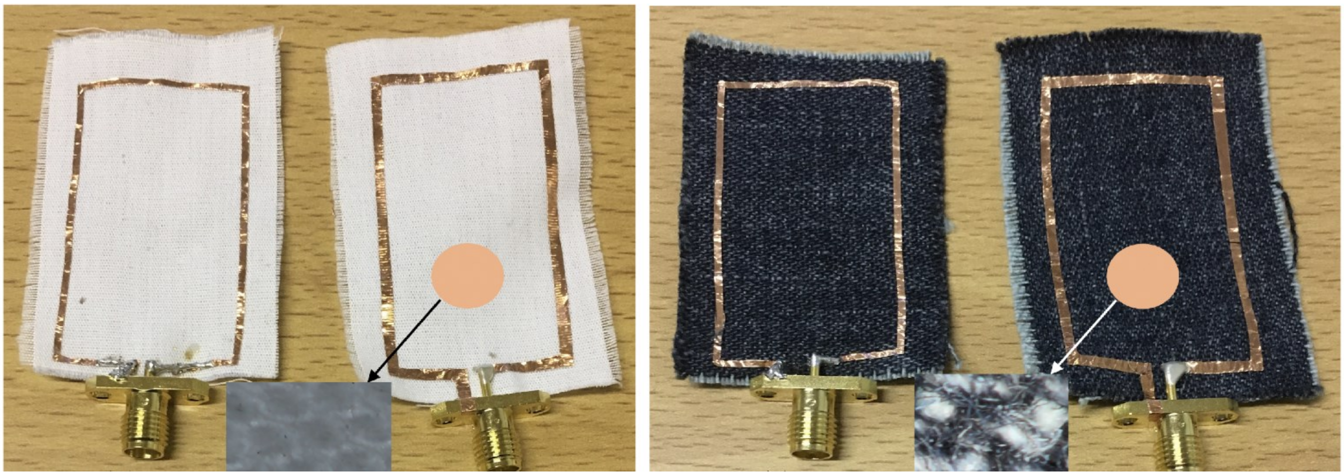

Fig. 3 Fabricated wearable loop antenna on various textile fabrics. Insets provide a zoomed-in microscopic view of fabrics. Adapted from reference [47], originally published under a CC-BY 4.0 licence.

Jeon et al. reported a self-powered wearable keyboard with a textile-based triboelectric nanogenerator (TENG). This low-cost triboelectric nanogenerator is a powerful sensing component for the interface device due to its energy-autonomous operation [48]. The integration of electronic components is accomplished by creating some connection between the textile substrate and the electronic elements. Often the textile material has separate functions, an example would be metal buttons as switches. Integration is performed at the textile levels, whereby the schemes can be partially attached to the surface and inside the material [40].

5 Applications of smart clothing

5.1 Sportswear

Nowadays, sports and health have become two closely related words, and smart sportswear combines these two concepts well, installing devices that can monitor the body's condition in real-time in sportswear to better help exercising so that people better understand their own bodies. In addition, smart sportswear also applies comfortable textile materials that are more suitable for people to exercise in multiple situations, local heating systems, ultra-flexible fibers, or scientific detection of the heart rate of professional sports. But in general, the use of smart clothing in sports is divided into four main areas such as remote monitoring, regularly monitoring, convenience and comfort and possibility of fitting [49]. In the case of remotely monitoring, an athlete can go about his or her daily routine and exercises, and the process of collecting information about parental health status and clinical findings does not require the presence of a medical person [49]. Being regularly monitored, the smart clothing allows identifying organs malfunction and determining the factors that affect the results of the exercise. Smart clothing offers great protection from injury. Moreover, it protects from fatigue in a unique way of early diagnosis of functional disorders. It helps to identify the first signs of pathological conditions, while the regular examination is not informative enough. Screening assignment of a functional status of one's body could be held in stages of stress and rest [50]. Convenience and comfort are of advantage in smart clothing because athletes feel comfortable and light, and smart clothing is visually indistinguishable from normal clothing. These factors make it possible to train with maximum performance [49-50]. The possibility of customization of clothing technologies allows updating further preferences of an athlete depending on available data – to correct mistakes, to change the intensity of training, etc. [51]. Figure 4 shows a T-shirt prototype that incorporates electromyography (EMG), a diagnostic recording system. By means of stitched electrodes, the electrical activity of the striated muscles is measured as voltage [52].

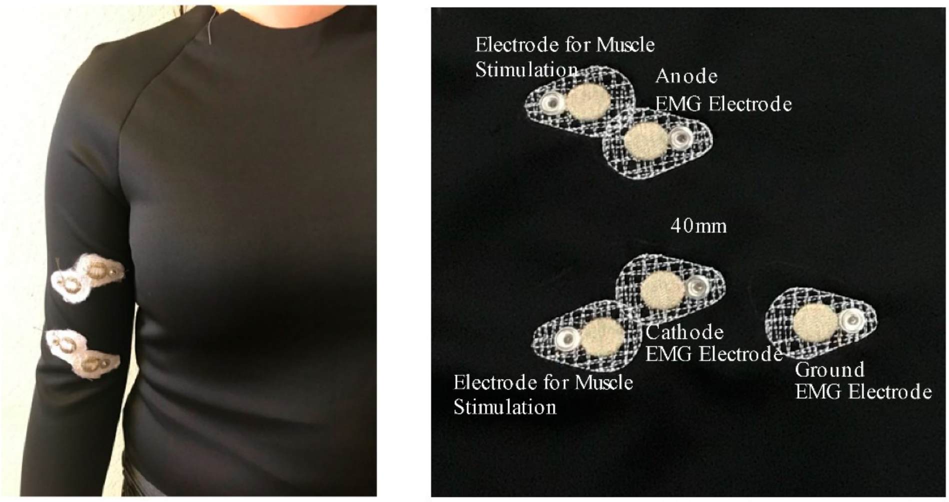

Fig. 4 T-shirt prototype with embroidered electrodes. Adapted from reference [52], originally published under a CC-BY 4.0 licence.

The Nadi X yoga pants can illustrate the combination of intelligence and clothing [53]. These yoga pants contain integrated tactile vibrations that gently pulsate in the body areas such as thighs, knees and ankles. These subtle signals give gentle instructions to the user to move in a certain direction and/or to hold the pose. The pulsations help users better focus and master proper posture as they perform their yoga workouts. Nadi X smart yoga clothes can provide feedback to the exerciser whether the posture is correct or not through vibration and haptic. The smart interaction function of the clothing can be more accurate and personalized for the user, making the clothing more intelligent. The pants sync with the user's phone via Bluetooth and provide additional feedback to the user via a companion app. Each workout is scientifically recorded, allowing users to observe their progress more visually. In addition, the Nadi X yoga pants are represented in a wide variety of sizes for men and women. These pants can be washed in a machine; the battery pack, which is attached to the back of the left knee, must be removed beforehand [53]. Another example of smart clothing with integrated sensor technologies represents a smart yoga suit from Electicfoxy, which uses electromyograms to measure the strains of muscles and body movements for use for sports and coaching functions [54].

Ambiatex T-shirt analyzes fitness and vital parameters by means of integrated sensors and monitors stress load. The collection and processing of data are carried out via TechUnit Box. The analysis of the user's individual anaerobic threshold (IAS) is compared with a lactate test at the doctor's office. The analysis of this data is done with the help of an iPhone or Android app and contributes to performance optimization and stress monitoring [55].

Komodo Technologies offers compression sleeves in various colors and styles that use electrocardiogram (ECG) technology to monitor heart activity. Heart rate data, exercise intensity, body temperature, air quality, UV radiation and the user's sleep patterns are monitored and can be used during sports, work or other activities [56].

5.2 Workwear

Today, smart clothing is not yet fully integrated into everyday working life, but as developments show, interest is growing steadily. In factories with special temperatures, workers wear work clothes that can intelligently adjust the temperature so that they can still feel comfortable and improve their work efficiency in hot or cold working environments [57]. In merchant talks, smart workwear can be exemplified by a smart business suit made by Samsung that can exchange digital business cards, unlock cell phones and interact with other devices [58]. Figure 5 shows an example of a tailored textile-compliant suit (E-TeCS) with wireless sensor technology. The sensors measure body temperature as well as heartbeat and respiration. The electronic strips are embedded in a flexible and dense textile channel [59].

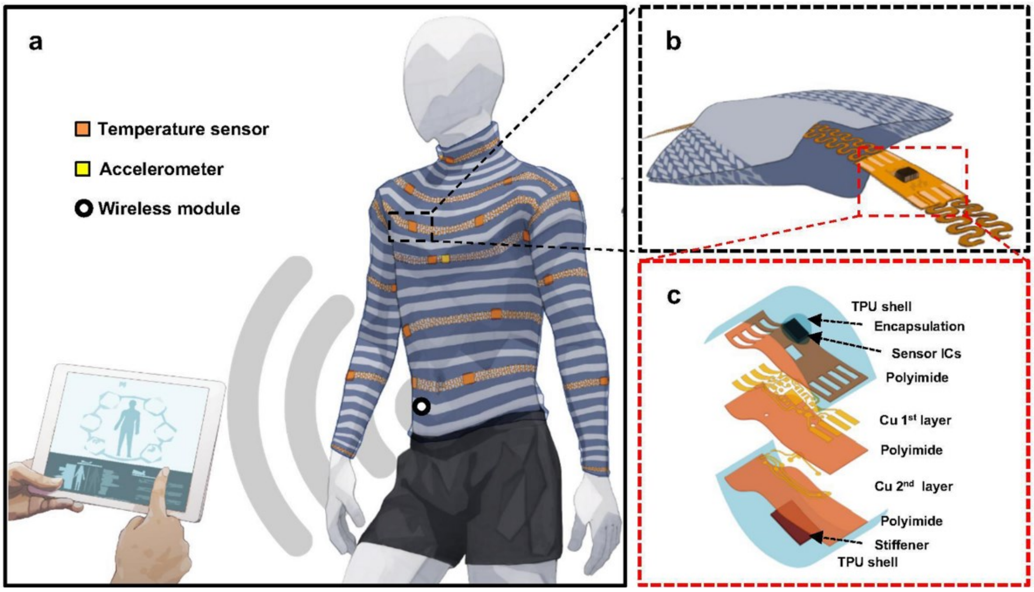

Fig. 5 A tailored, electronic textile conformable suit (E-TeCS) for distributed sensing wirelessly: (a) suit (E-TeCS) prototype; (b)an integrated sensor in textile; (c) schematic structure of the sensor. Adapted from reference [59], originally published under a CC-BY 4.0 licence.

Smart clothing with an intelligent monitoring function provides technological support for people to exercise reasonably and live a healthy life. It then works well to help people understand today's outdoor conditions and prepare in advance when businesspeople meet on the golf course [60].

The Rogatis smart suit uses an NFC (Near Field Communication) tag, which is integrated into the jacket pocket and automatically unlocks the phone when it is taken out of the suit pocket. In addition, this smart suit allows sending e-mails and switching smartphones to mute or block incoming calls [61]. This tag connects to the user's mobile device to open apps or exchange business cards over Ethernet. The suit can be adorned with Samsung's Perfect Wallet and cardholder, which opens various NFC functions via mobile apps [62-63].

5.3 Healthcare

Samsung is rapidly developing the field of smart clothing and has already introduced its Body Compass sweatshirt to monitor biometric data. In addition, a golf shirt with Bean Pole Golf was presented, which is able to monitor the environmental conditions and UV values. Intelligent monitoring function mainly refers to the ability to accurately collect the human body's heart rate, electrocardiogram, blood oxygen, body fat, breathing, pulse, temperature, humidity and pressure, step count, electromyographic signals and other physiological characteristics of information, and can analyze this information through the information processing module, monitor whether the human body is at a healthy physiological level, and provide a reference for the prevention and deployment of certain diseases [65]. Smart clothing with intelligent monitoring function is mainly used in the field of health care and sports monitoring; the elderly can get their own health data, conscious prevention and early detection of disease, while sportsmen can keep abreast of their physical state and adjust the intensity of exercise [66-67]. Figure 6 shows a stretchy bra for early detection of breast cancer. Palpreast is an expandable bra for early detection of breast lumps. An inflation system consists of four independent air chambers centered on the breast and a pressure-sensitive sensor textile, which can detect tissue thickness and distinguish between healthy and abnormal tissue [68].

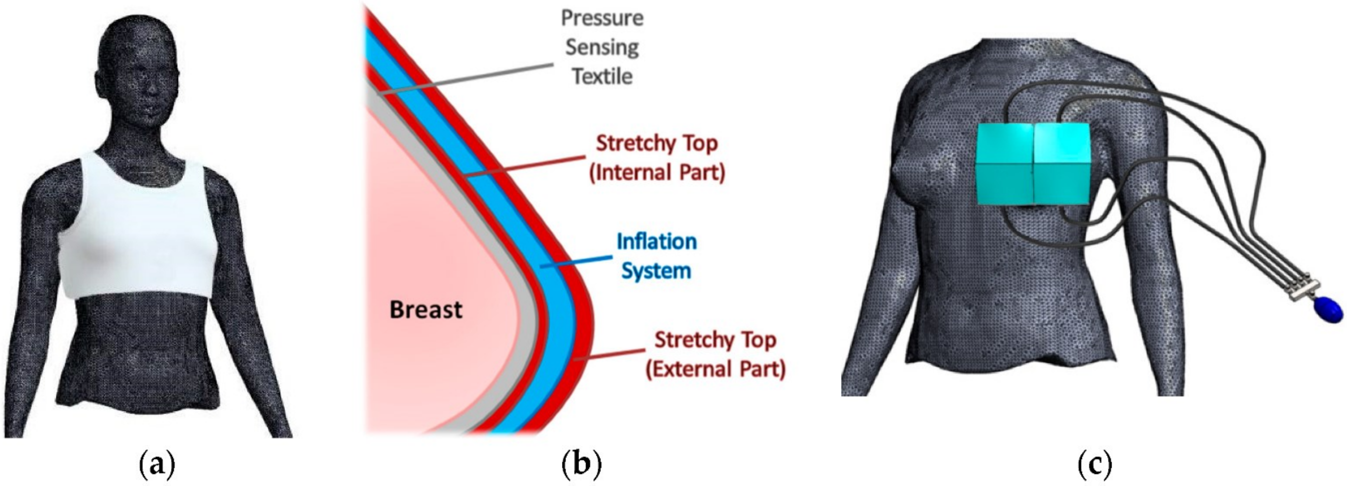

Fig. 6 (a) Stretchable bra for early detection of breast cancer; (b) four independent air chambers centered on the breast; and a (c) pressure-sensitive textile sensor. Reproduced from reference [68], originally published under a CC-BY 4.0 licence.

Smart clothing is still in its infancy and practical applications in hospitals and other care facilities are still relatively limited, but the need is high and current inventions will become mainstream healthcare in the near future [69]. The main use of smart clothing in the healthcare sector is at the one hand to track diseases or conditions of patients, as well as to boost health insights, and on the other hand to reduce the costs for medical treatments and give the patient a more comfortable stay at the doctor or hospital [70].

An example of an application in this field is the heart rate monitor front end. It is a biomedical sensor that is directly implemented in the textile (for example in the blanket or the hospital clothes for patients). This sensor measures, extracts, amplifies and filters small biopotential signal and communicates them directly to a monitor where everything can be read off by the doctor or other personal [71]. This conductive sensor can be embroidered on textiles with conventional table sewing machines by stitching electrically conductive metal fibers made of silver, copper, nickel or stainless steel onto the surface of textiles using a computer program. It is also possible to cover the conductive fibers with yarns and incorporate them directly into the fabric manufacturing process, and such textiles with conductive threads can even be washed [71].

Another example is the company Visseiro which created a sensor particularly tailored to elderly people in need of care, measuring the vital data of the heart and lungs as well as sitting behavior. This is done while sitting on a cushion or (nursing) chair with integrated software. The advanced algorithms analyze the collected data and calculate an individual health score. In an easy-to-understand manner using an app and web platform, relatives and caregivers can monitor the objectively determined state of health online at any time [72].

5.4 Military protective clothing

Another interesting area in smart textiles that is continuously growing are smart textiles used in the military context. Figure 6 shows a schematic representation of Nafion films with openable flaps that mimic the thermoadaptive function of human skin. Nafion film flaps open and close automatically in response to changes in humidity and temperature. Advantageously, it does not require an external energy source and allows individually adjustable physical comfort of the wearer [73].

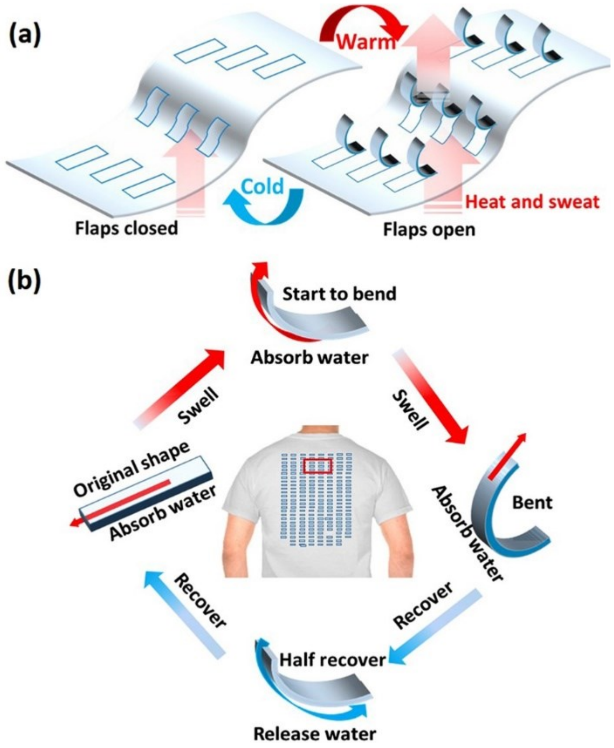

Fig. 7 Smart clothing with imitation of human skin function. (a) Schematic representation of Nafion films with flaps mimicking thermoadaptive function of human skin; (b) reversible swelling, bending, release and recovery behavior of Nafion flaps. Adapted from reference [73], originally published under a CC-BY 4.0 license.

There the two main areas which are energy production and health status monitoring. Energy production with the help of smart textiles in military wear can be done in two different ways. One option is to integrate wearable solar panels in soldiers' everyday wear, for example, on the helmet or the head of a soldier as well as the uniform or the backpack that is carried anyway and mostly presented to the sun. This technique is developed and produced by the U.S. Army Communications-Electronics Research, Development and Engineering Center (CERDEC) [74]. This is a center from the US Army that is responsible for the US Army's information technology and integrated systems [75]. An alternative way to generate energy with the help of smart textiles in the military context is done with the help of a bionic power product composed knee brace. This is integrated into the soldier's uniform in the knee area on both sides. The kinetic energy that is produced while walking or running can then be transformed into electric energy. With this application, an average of 12 watts of electricity can be generated while walking [76]. A problem that occurs while using both systems is that the produced energy cannot really be stored. Using batteries is, up to now, too uncomfortable and unpractical for the soldiers since batteries take a lot of space and are too heavy to carry around additionally to the general luggage of a soldier. That means, that in the best case the energy is used at the moment it is produced [77]. Another area of application for intelligent textiles is military clothing, in which the health status of soldiers is continuously monitored. Integrated sensors in the helmet and a comprehensive vital sign system register the person's position and movement as well as heart and breathing rates [78]. In addition, the fluid intake, skin temperature measurement and sleep behavior are constantly checked and displayed on the monitor. When all of this data is collected, the vital parameters of soldiers can be monitored and occurring problems as well as bullet penetration can be detected [79-80]. But there are also other sensors that are integrated into military clothing for the safety of soldiers and to protect them from gunshots [81-82]. A special yarn is integrated into the soldier's uniform, which reacts to a defined laser beam. This laser is placed on the army's weapons. When a soldier points his weapon at a soldier from his own group, the laser attached to the weapon lights up the uniform and immediately gives the shooter a signal that no shooting is allowed [82].

5.5 Fashion

The "wearable love" collection from H&M Lab in 2020 includes a denim jacket with which touches are sent via app and Bluetooth. Flexible sensors are incorporated into the shoulder area of the jacket, and Bluetooth can be used to send various touch patterns that are supposed to feel like real touches [83]. This denim jacket is based on the technology of Boltware, a Wear It Berlin GmbH startup from Berlin, which produces boltware special clothing for sports and work. Athletic products include integrated performance tracking features and an automatic reporting function for dangerous accidents [84]. The designer Pauline van Dongen developed Wearable Solar Dress and Wearable Solar Coat with integrated solar cells that can be worn invisibly [85]. A chameleon jacket was developed by Norwegian studios for the interactive product designs Drap og Design, which change their color according to the colors that the wearer touches. This jacket has integrated LED lights and a color sensor and is controlled by an Arduino microcontroller [86]. The designer Anouk Wipprecht has developed a bionic 3D-printed dress with the function of self-defense. The dress has a spider-like design and incorporates an Intel Edison chip to read biosignals and simulate the territorial defense of a spider. The robotic arms respond to the wearer's motion and respiration sensors [87]. The designer Richard Nicoll has developed a jellyfish dress made of fiber-optic fibers, which are integrated into fabric and illuminated [88]. Fashion designer Lauren Bowker developed a collection of clothes that change color with the wind. She used a color-changing ink that changed color from yellow to black depending on the amount of pollutant particles in the air [89].

6 Smart clothing components

An intelligent textile system consists of main components such as sensors, actuators, communication devices, data processing units, and power components [90]. The structure of the intelligent textile system is shown in Figure 8.

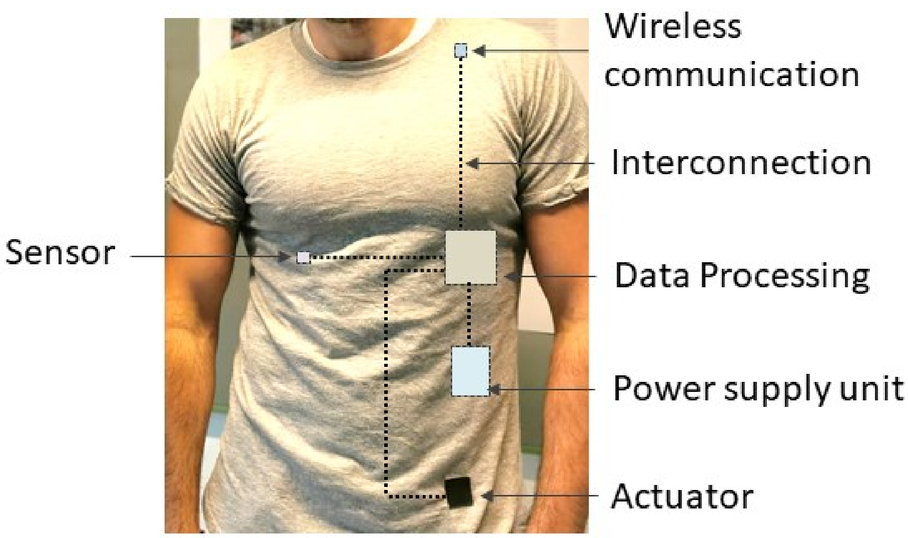

Fig. 8 Illustration of smart clothing components: sensor, actuator, data processing unit, connecting elements, communication device, and energy component.

These functions of the smart clothing should be appealing in terms of comfort, durability and should withstand washability and the usual textile care procedures without compromising the functionality [91].

7 Requirements of smart clothing

Smart clothing has some requirements, which will allow unhindered and long-lasting use of such clothes. The choice of material is the most important decision, as it affects the technology of production as well as the basic properties of the garment, such as softness, the life cycle of the final product, the elasticity of fabrics and washability [92]. The wearable characteristics of smart devices require them to be miniature, lightweight, and well concealed. To make the product really integrated into the user's daily life, the pursuit of the design of humanization and comfort to avoid the product bringing discomfort is a major focus. A new element is an interaction based on the measurement of subconscious behavior and state of physiological condition, posture, or movement during everyday activities of a user. Also, the robust function and information quality of smart clothing are important [93,94].

For smart clothing to become popular, it is necessary to take into account the requirements of comfort and practicability [95]. In addition, electronic parts must be harmoniously integrated into the style and design of the garment. The design, for its part, must fit efficiently into the technical specifications. It is necessary to keep a balance between the technical development, the comfort and practicality of the clothing and its cost, so that smart clothing remains competitive in the market [96].

Breathability and wearing comfort play a major role in the selection of clothing materials. The balanced interaction between heat dissipation of the human body and a good ventilation performance leads to a comfortable feeling and efficient physiological clothing comfort of the user. In addition to the correct selection of clothing materials, the structure and aesthetic design of the clothing are also important. The structure is composed of a combination of different parts of the clothing as well as the thickness of the materials and total weight of the smart clothing parts. Ideally, the smart clothing part should be light, but very well protected from heat, cold and moisture, breathable to avoid overheating of the body and easy to clean and wash for maximum comfort.

The basic idea of a new generation of wearable systems is that monitoring devices are not only attached to clothing but sensors and electronics are integrated into the clothing itself [97]. Textile technologies, which can be called “electronic textiles”, or in other words “e-textiles”, are fabrics made of filaments woven together in different ways that are capable of interacting with an external environment, such as the human body [98]. Continuous research and development of flexible sensing technology, so that the sensor and clothing fabric are cleverly combined, help maintaining the softness and comfort of clothing while improving the sensitivity of internal and external environmental perception. Smart clothing can give the possibility to be everywhere, do everything and know everything. To implement this possibility in daily life, the technology has to be small as possible to be wearable [99].

8 Current state of smart clothing

When looking into everyday life, smart clothing and e-textiles are not so often used because they are currently not so widespread. There are several reasons for this, such as these smart clothing products are not yet well known, are not mass-produced and available everywhere, have relatively high prices, are not trendy, mostly not aesthetically designed, are not “must have items”. In addition, some questions about functionality, washability, durability of use, use of different software for data transfer and complexity of use, risk to health from electromagnetic radiation, etc. still need to be answered [100].

Currently, customers do not yet understand smart clothing, and these products cannot yet completely replace smartwatches or smartphones, for example. Customers do not see the need to buy an expensive smart clothing item, because they do not see the added value they get when they compare for example the functions of smartphone and smart clothing [100]. For this to happen, the technology must be further developed, there must be an understanding of the product's features, and these smart clothing items maybe must be available as a mass product. The need for smart products should be created and more marketing activities can improve awareness and understanding of the added value of such products. Various textile technologies are used for the integration of electronics in smart clothing. For example, conductive yarns are woven into textiles and the question arises as to how many washing cycles these textiles can withstand without impairing the conductivity. The question of safe charging of electronic parts is not yet mature, because the electronic parts are already relatively small, but external batteries are necessary to ensure the functionality and batteries are usually relatively lumpy.

Currently, smart clothing parts are not necessarily sustainable because many of them cannot be washed or the washability of these parts is limited. In addition, the recycling issue of smart clothing parts should be addressed, because they are a mix of different materials, conductors, and electronic parts, etc., making recycling and reuse difficult.

The use of smart clothing and e-textiles is currently in the military, medical and healthcare, and sports and aerospace sectors, rather than in the everyday lives of the general public. Innovative products are currently only of interest to a relatively small group of innovators who are enthusiastic about technology and buy these smart clothing items. However, as this research shows, the use of smart clothing will increase in the near future and will be more integrated into everyday life than it is now.

9 The future of smart clothing: possibilities and challenges

The widespread commercial introduction of smart garments is not yet taking place everywhere, also due to the still partly unsolved problems such as limited washability and dependence on energy storage media such as batteries. In addition, the textile industry and manufacturing machinery and processes are not suitable for smart textiles and garment manufacturing. Moreover, smart textiles and smart clothing currently still have a relatively high price and are relatively little known to a wide audience, and the benefits are not yet in the foreground.

As illustrated by the number of publications in this field, the interest of scientists is constantly increasing and new developments in smart clothing are reported. These difficulties still pose some current barriers to the widespread adoption and use of smart clothing. But according to forecasts, smart clothing will play a major role in people's everyday lives in the near future.

Soon these techniques will be available to a greater number of people, because as production continues to develop and improve, prices will stagnate, making them more affordable for many people. In addition, the accuracy and comfort of the techniques in the areas used will evolve and improve over time. The combination of the techniques used with mobile applications can provide the data, for example, to monitor the physiological status of people at risk in real-time or to collect other real-time data that can be used in many other areas [101].

Smart textiles and smart clothing are also becoming increasingly important for the fashion industry. Technological developments such as color changes and the integration of conductive sensors etc. could revolutionize the way designers think about fashion [102]. Smart clothing with a fashionable design, functionality and comfort are of great interest for future consumer needs. In the near future, smart clothing will be particularly important in the areas of sports and health management, leisure and entertainment. Smart clothing will constantly measure heart rate, breathing, blood pressure, body temperature, sleep behavior, etc. in order to monitor vital functions and to warn the wearer in good time if the data of physical signs fluctuate drastically and a heart attack or deficiency occurs. This will minimize the likelihood of dangerous situations.

By exploring and recording the changes in nature, an automatic temperature adjustment of the environment is carried out combined with health care in order to manage leisure and entertainment. Smart clothing can play music from the radio as well as store music in the chip and play it off as required. A running route can be planned and mapped and sports training data can be saved in the cloud in order to carry out sports exercises more efficiently. The wearing comfort of the clothing can also be controlled by using an intelligent fabric to expand or contract using electrical signals, for example, to expand or narrow the waistband of the trousers or to change the color of the clothing as desired.

In smart clothing, both in terms of hardware and software, there is still a lot of room for improvement. Users are not satisfied with the simple needs of fashion; unique features and personalized requirements are increasingly high, the addition of intelligent elements undoubtedly fits the current demand for clothing. Smart clothing on the one hand needs to diversify its functions to meet the multiple needs of users, and on the other hand, needs to be refined and specialized in its field to truly address the core concerns of users. Smart clothing will continue to integrate a variety of data, applications, and services to create an integrated, personalized smart wear experience for users. In terms of interaction, smart clothing will use diverse interaction methods, such as voice recognition interaction, gesture interaction, biofeedback interaction, situational awareness interaction and even brain-computer interaction. In terms of energy supply, to provide continuous and stable energy supply to smart clothing, smart clothing will be a more sustainable energy source such as solar, wind, temperature, and physical energy.

Like any other development or new area, the future of smart clothing brings of course challenges and possibilities with it. At the moment the washing and drying cycles are too harsh for the used electronics, sensors or other techniques [103]. That means that the applied electronics and sensors have to be removed before washing and attached again after the washing and drying process. This is always a huge extra effort that makes it unpractical and time and money-consuming. An important point is the affordability of the product, as smart clothing should not be an item that only certain segments of the population can afford. Also, the life duration of the produced goods is not the best at the moment. But all of these problems will be solved within the next years since these are minor difficulties that can be solved by further development and research as well as practical experiences [104]. Some media boldly predict that soon, the boundary between digital products and clothes will become increasingly blurred, with future electronic products perfectly “hidden” in clothing, while future clothing will be transformed into a computer that can be “worn” on the body.

It is expected that companies from different industries will cooperate much more in the production of smart clothing, as is the case now. The manufacturers of software will cooperate with electronics sharing manufacturers as well as with textile companies, which will cooperate with manufacturers of conductive yarns, wires, etc. to produce smart clothing in cooperation and together form more sustainable value chains. It is also noted that the development and innovations in smart clothing and new innovative textiles and materials will drive the further development of existing textile techniques, and new machines, equipment, tools, processes and production lines will be developed to process smart clothing and meet demand. It is likely that with the development of new intelligent materials and new cleaning methods, the problems of washability will be solved. Also the microelectronic parts will be further developed and will not be so sensitive to disturbance or cleaning processes. The still clumpy baterries and energy storage devices will become much smaller and more efficient and will not affect the clothing comfort. According to research, the market for smart clothing and e-textiles will grow steadily in the next few years, revenues for companies are expected to increase, and smart clothing will be widely used and integrated into everyday life.

10 Conclusion

Smart clothing helps understanding and recognizing changes in the human body under the influence of the environment and physical activity. It is modern clothing that can help the body to adapt to changes through feedback mechanisms. With the continuous development of science and technology, it has integrated biochemical technology, electronic information, human-computer interaction and bionic technology, and gradually developed into a product of multidisciplinary research.

Nowadays, intelligent clothing has been applied to sports and health, medical and health care, military equipment, security and protection, life, and entertainment, and towards the direction of more comprehensive functions, more comfortable wear, more diverse technologies and more intelligent materials. In terms of technology, smart clothing will be more miniaturized and contain flexible batteries, sensors, chips, screens and other hardware, low-power processors and batteries with improved lifetime. Functional applications will be enriched, while at the same time more attention will be paid to the overall clothing comfort. By improving the combination of sensors, power and other electronic devices and fabrics, the softness of the electronic devices will be improved, making smart clothing more comfortable to wear. To sum up, smart clothing is a class of clothing that can sense changes in the human body and the environment and respond and adjust to such changes through feedback mechanisms. Smart clothing is a research hotspot in the textile and apparel industry. With the continuous development of science and technology, smart clothing incorporates biochemical technology, electronic information technology, human-computer interaction technology, bionic technology, and other technologies, and gradually develops into a product of multi-disciplinary research.

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