Chapter

Smart Textiles Testing: A Roadmap to Standardized Test Methods for Safety and Quality-Control

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Abstract

Test methods for smart or electronic textiles (e-textiles) are critical to ensure product safety and industrial quality control. This paper starts with a review of three key aspects: (i) commercial e-textile products/technologies, (ii) safety and quality control issues observed or foreseen, and (iii) relevant standards published or in preparation worldwide. A total of twenty-two standards on smart textiles – by CEN TC 248/WG 31, IEC TC 124, ASTM D13.50, and AATCC RA111 technical committees – were identified; they cover five categories of e-textile applications: electrical, thermal, mechanical, optical, and physical environment. Based on the number of e-textile products currently commercially available and issues in terms of safety, efficiency, and durability, there is a critical need for test methods for thermal applications, as well as to a lesser degree, for energy harvesting and chemical and biological applications. The results of this study can be used as a roadmap for the development of new standardized test methods for safety & quality control of smart textiles.

Keywords: smart textiles, wearable electronics, test methods, quality control, safety, efficiency, durability, electronic textiles (e-textiles)

1. Introduction

The smart/electronic textile market has recently exploded, mostly driven by personal healthcare. The term “smart textiles” refers to the “smart functionality” of a product, whereas “electronic textiles” (e-textiles) refer to the “hardware and/or technology” that is responsible for the smart functionality [1]. The market size of smart textiles already reached USD 4.72 billion in 2020 with Asia-Pacific countries leading the chart followed by Americas and Europe [2]. Vista Medical Ltd. (Canada), Myant (Canada), Interactive Wear (Germany), Schoeller Textiles (Switzerland), Intelligent Clothing (England), Google (US), International Fashion Machines (US), Textronics (US), Gentherm Incorporated (US), and Sensoria (US) are the major key players in the smart textile industry.

The convergence between textile substrates and conformable electronics like embedded sensors or actuators has given rise to wearable smart/e-textiles. E-textiles can augment the level of protection, comfort, and physiological performance of humans, with applications in many industries, including medicine, protective clothing, military, and automotive. A few authors have analyzed these current and potential applications. For instance, Honarvar and Latifi described the components, structures, and major application areas of smart e-textiles, including ambulatory measurements for patients with cardiovascular diseases, nonwovens for electromagnetic interference (EMC protection) for security, protective GPS-suits for military, bleeding sensor threads for surgeons, and flexible electronic keypads for dialing phone numbers [3]. Ismar et al. explored the use of e-textiles for futuristic clothes [4]. Dolez et al. analyzed the potential of smart textile technologies for occupational health and safety (OH&S) [5]. Finally, Stoppa et al. described different biomedical smart textile projects conducted within the European Commission's 6th and 7th framework programs: WEALTHY, MyHeart, BIOTEX, PROTEX, STELLA, OFSETH, CONTEXT, WearIT, and PLACE-it [6]. This convergence between clothing and electronics could pose some critical challenges for regulatory bodies, including US Food and Drug Administration (FDA), Health Canada, and National Institute for Occupational Safety and Health (NIOSH). Appropriate quality control methods are a critical tool for them to ensure that e-textiles do not to endanger users' health, safety, and privacy among others.

The lack of standardization of e-textiles is also considered one of the primary restraining factors for industrial growth. Even though the e-textile industries have generally been keen on designing products with improved safety and performance features, their efforts may not have met market expectations due to the current lack of dedicated standardized test methods. The two main disciplines at the root of e-textiles - textiles and electronics - are so much at odds with each other that dedicated standardization methods for smart/e-textiles are critical. However, progress in this area is lagging behind in comparison to the rapid pace of technological innovation. In this chapter, we will highlight critical challenges and provide some suggestions for the development of standardized test methods for smart/e-textiles.

2. Overview of smart/e-textile products and major barriers to market entry

As consumer electronics are marching towards the era of the Internet of Things (IoT), so are smart/e-textiles. Gradually, conformable electronics are embedded within textiles of various configurations to offer an on-body platform for pervasive computing, especially for healthcare and OH&S applications. Examples include a smart trouser for forest workers that can detect the proximity of chain saw and automatically turn it off [5]; industrial protective gloves that alert users of air toxicity by changing their color [5]; power vests to prevent unsafe movements of caregivers while lifting heavy weights [7]; and Myant's recent VOC (volatile organic compound) sensing facemasks to detect airborne infectious agents [8]. Also, smart textiles have been designed for protection against sexual assaults, with the SHE (Society Harnessing Equipment) anti-rape lingerie that can deliver a 3800 kV shock [9]. On a lighter note, Microsoft patented a smart cloth that alerts a user of an incoming text message or daily activity reminders, by generating a mild electric shock to the body [10].

A survey of technologies, solutions, and products based on smart textiles and flexible materials was done in 2017 [5]. The different technologies, solutions, and products in terms of sensors and actuators identified were grouped into seven categories based on the input signal or stimulus for the sensors and the output signal for actuators. These categories are thermal, mechanical, chemical/biological, electrical, physical environment, optical, and power. **Figure 1** shows the distribution of

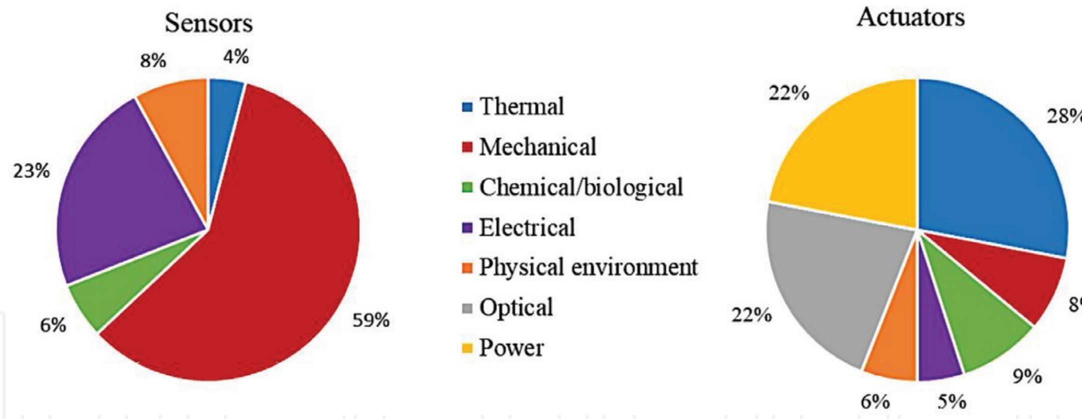


Figure 1.
Distribution of technologies, solutions, and products relevant to smart textiles and flexible materials as a function of the stimulus for sensors (left) and output signal for actuators (right) [5].

the technologies, solutions, and products based on smart textiles and flexible materials identified by the researchers in these different categories. In the case of sensors, the dominant category is associated with a mechanical stimulus, with 59% of the sensors. Electrical sensors account for 23%. In the case of the actuators, thermal, optical, and power outputs represent each about a quarter of the technologies, solutions, and products identified.

However, before the mass adoption of smart/e-textile products is possible, some burning questions need to be addressed: for instance, what is a safe electrical shock, both for user alert and assailant deterrence? Could a malfunctioning smart garment prevent activating a safety emergency shut-off system? What about potential privacy issues associated with the data generated by e-textiles? In an attempt to standardize their assessment of wearable electronic product performance, a group of electrical engineers evaluated the safety performance of wearable energy harvesters based on the device failures and user-related hazards [11]. However, to date, no one has provided a response to the questions customers could legitimately ask for the different applications smart/e-textiles are aiming for.

For instance, according to experts, the lack of standardization and quality control poses the highest barriers to smart textiles entry into the healthcare market (**Figure 2**) [12]. Since wearable electronic components are often worn close to the body, special attention is required to prevent health hazards. There are also potential issues of efficiency associated with the interconnections between the different components. The lack of standardized processes for welding, soldering or glueing for instance can significantly reduce the performance, durability, esthetic, and

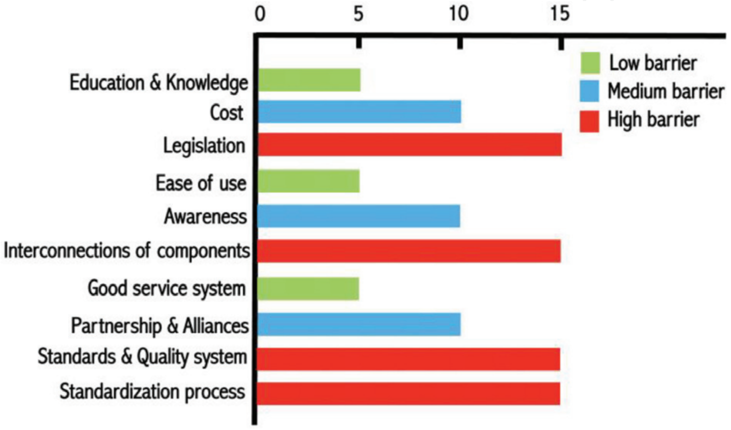


Figure 2.
Barriers to entrance of smart textiles in the healthcare market (based on data from [12]).

hand-feel of the product. Other barriers include product cost, public awareness, lack of education and knowledge [12]. Strategic industrial partnerships and multidisciplinary alliances among key players in textile, electrical, and biomedical engineering can positively impact the product design and test method development processes.

3. Review of different issues reported or foreseen

This section will describe different issues, reported or foreseen, associated with the durability, safety, and efficiency of smart/e-textile products, including health monitoring apparels, protective clothing, automotive actuator textiles, and textile-based physiological sensors.

3.1 Durability

Electrical elements embedded into textile structures to produce e-textiles include electronic circuits, electrodes and printed tracks. They must be extremely rugged, robust, and durable because of their regular exposure to mechanically demanding environments [13]. The issues of durability reported with e-textile products are discussed in the next sections.

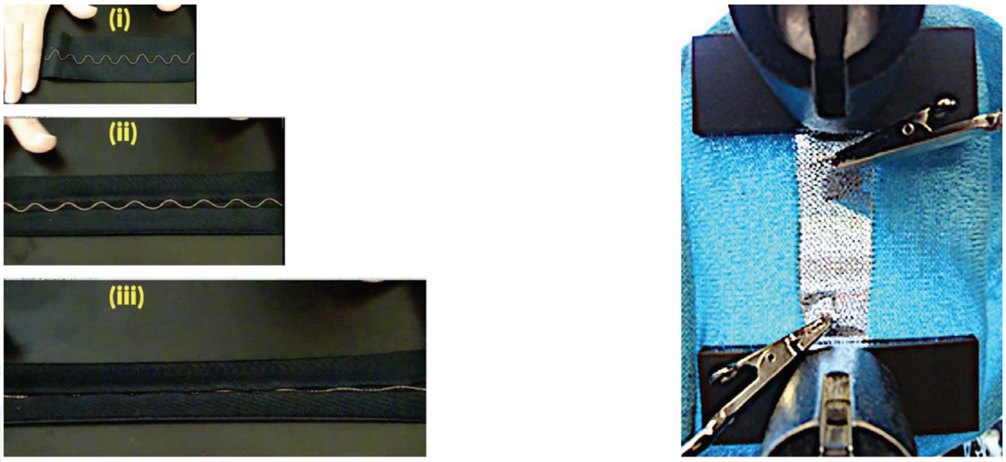
3.1.1 During the manufacturing process

A first aspect of durability deals with the e-textile manufacturing process itself. For instance, conductive yarns embroidered on a textile may be damaged by three dominant forces: tension, bending, and shearing [14]. In particular, conductive fibers generally exhibit a low bending radius [15]. However, for flexible display applications, they would be typically subjected to bending radii lower than 1 mm. They also have to withstand friction stresses associated with the embroidery operations. In the case of weaving, fibers must possess the capacity to withstand bending radii as small as 160 μm and 20% tensile strains.

3.1.2 Effect of biomechanical stresses during wear

An apparel product is subjected to large biomechanical stresses during wear, including during donning and doffing. For example, a research conducted with Canadian combat clothing showed that maximum stresses of 2410 and 2900 N/m occur during squatting across the back seat of trousers and coveralls, respectively [16]. Other movements like when bending elbows (for sleeves), bending knees (for trouser legs) or bending over exerted significant stresses on combat clothing of Canadian Forces. If the smart/e-textile product is not robust enough to withstand such biomechanical stresses, they will be easily damaged and experience a loss in functionality like sensing, communication, data-transfer or power supply. Such problems of loss in functionality could cause safety issues for soldiers or first responders in the line of action. Using stretchable connection and electrode designs could allow accommodating body-induced stresses applied on e-textiles. **Figure 3** displays examples of strategies to produce stretchable electro-conductive textiles.

Researchers conducted tensile and bending resistance tests to assess the durability and elastic properties of smart/e-textiles. For example, PEDOT:PSS ((poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate)) dyed cotton and silk yarns exhibited a tensile strength of 260 and 136 MPa with a conductivity of 12 S/cm compared to 305 and 157 MPa for the pristine (uncoated) cotton and silk yarns,



(a)

(b)

Figure 3.
Examples of stretchable electro-conductive textiles. (a) Elastic behavior of a conductive yarn (white on the pictures) under increasing deformation (i) undeformed, (ii) medium deformation, and (iii) high deformation. The conductivity was maintained even at high deformations. (b) Experimental set-up to measure the electrical resistance of a knitted electrode under stretch in a mechanical test frame.

respectively [17]. The conductive polymer coated silk yarns showed a robust electrical performance, displaying a reduction of conductivity of around 50% after 1000 bending cycles. Using a fabric test tester, Qui et al. measured the durability of a power generating textile fabric [18]; it did not exhibit any measured degradation after 10000 bending cycles of mechanical stimulation, showing superior durability. **Table 1** displays different test methods used by researchers to assess the durability of textile resistive heaters (**Table 1**).

3.1.3 Effect of surface phenomena in service

Besides biomechanical stresses, different surface phenomena such as wear, corrosion, chemical contamination could destroy the transmission functionalities of smart textile components like optical glass fibers [28]. For instance, **Figure 4** illustrates the effect of abrasion on a smart/e-textile webbing (white on the left image (a)) than includes conductive yarns. The multimeter on the right image (b) records the electrical resistance after successive series of abrasion cycles.

To simulate wear behavior, different mechanical tests can be conducted on textiles, for example to measure their abrasion resistance [29]; a lower abrasion resistance would potentially indicate a poor durability of the electrical functionality for conductive tracks on smart textiles. Recent work on a graphene-coated aramid fabric reported a resistance of up to 150 abrading cycles before the complete loss of electrical conductivity [30]. The stability to wear of a power generating textile fabric was analyzed after prolonged use of up to 15 days [18]. The fabric was successful at lighting up an array of LEDs under different dynamic conditions: raising hands, shaking clothes, and human running.

Durability against environmental degradation is another critical factor for smart textiles. For instance, silver-plated textile electrodes may lose their functionality if exposed to air for a longer period because metals are prone to atmospheric corrosion, including silver [31]. When silver is exposed to atmospheric pollution, the surface tarnishes due to a reaction between silver and reduced sulfur compounds in the ambient air [32]. As a result, a dark layer of Ag_2S (silver sulphide) is formed over the silver plating. Sulfur releasing bacteria could also be present in our washing machines, which may lead to a secondary sulfidation of textile silver electrodes [33].

Conductive elements	Test condition	Form factor	Durability test method	Study
Carbon nanotube (CNT) ink	—	Printed element	Tensile strength	[19]
Silver filament	80, 100, and 120 °C in oven for 264 h	Yarn	Tensile strength	
Silver yarn	65% RH and 20 °C as per EN ISO 2062:2009	Plain, rib, and interlock fabric	Stretchability	[20]
Stainless steel yarn	—	Plain and interlock fabric	Stretchability	[21]
Copper nanowire -polyurethane film	—	Nylon glove with the printed film	Stretchability	[22]
LIG (Laser Induced Graphene) on polyimide film	—	LIG film in contact with copper tape and Ag-paint	Bending test	[23]
Composite ink (graphene-tourmaline- polyurethane)	—	Printed heater on woven cotton wrist band	Abrasion resistance	[24]
CNT-polypyrrole polymer	—	Polymer coated cotton yarn	Bending test	[25]
Multiwalled CNT	—	Coated cotton woven fabric	Bending test	[26]
Carbonized modal knit encapsulated with Ecoflex silicone rubber		Weft knitted fabric	Bending test	[27]

Table 1.
Methods used to assess the durability of resistive heating textiles.


(a) (b)

Figure 4.
Abrasion testing on a white webbing with conductive yarns (a). A multimeter measured the change in resistance after successive series of abrasion cycles (b).

Salt from body sweat during workouts or from seawater in marine applications may also corrode metallic elements of smart textiles [34].

3.1.4 Thermal resistance

Resistance to heat is a critical factor for electro-thermal e-textiles, for example heating textiles. The heating components and the material in contact have to be able to sustain the heat generated with in operation without losing their conductivity, strength and other performance, and without getting on fire or melting. For instance, Liu et al. characterized the impact of heat exposure on Ag fabric heaters [35]. The study reviewed the heating performance of three different knitted fabric heaters, viz., plain single jersey (PSF), ribbed stitch (RSF), and interlock knit (ILK), fabricated with silver plating compound yarns (SPCYs) and polyester staple fiber spun yarns (PSFSYs). After 264 h of prolonged heating of the SPCYs in an oven at three different temperatures, 80, 100, and 120 °C, the electrical resistance of the SPCYs were evaluated. The resistance of the heater increased by ∼17% and ∼ 75% after the 264 h aging period at 80 and 100 °C, respectively. After 24 h of aging at 120 °C, the resistance exceeded the measuring range of the multimeter. In addition, the textile structure used may affect the thermal resistance of the system. For example, it was reported that a fabric woven with Ag-coated nylon and cotton yarn powered at 15 V exhibited different degradation temperatures depending on the weave structures: 69.8 °C for plain weave, 80.6 °C for twill weave, and 103.5 °C for sateen [36].

3.1.5 Resistance to washing

Washability is a massive barrier to successful commercialization and widespread adoption of e-textiles. It is a critical concern for e-textile users as the washing and drying processes subject the product to damaging conditions and could eventually destroy the connectivity between the electronic components or the electronic components themselves [37]. Chemical stress (detergent, surfactants), thermal stress (washing/drying temperature), solvent (water), and mechanical stress (e.g., friction, abrasion, flexion, hydro-dynamic pressure, garment twist) are the four dominant forces that could damage electronic components during washing cycles. A protective layer is typically used to protect the smart textile or its electronic components from getting damaged or exposed during laundry. Polyurethane (PU) is largely used as a waterproofing encapsulation layer for e-textiles [38]. It has the great advantage of being flexible and stretchable and can accommodate the stretch of the fabric underneath. Polypropylene thin films have also be laminated to provide protection to metallized polymer films on e-textiles against repetitive washing and abrasion [39]. However, the encapsulation may not be durable. For example, the extremity of metal wires encapsulated in an e-textile product could damage the encapsulation layer due to their intrinsic rigidity and configuration geometry. **Figure 5** shows how the extremity of soldered metal wires pierced through a PU lamination after repeated washing cycles.

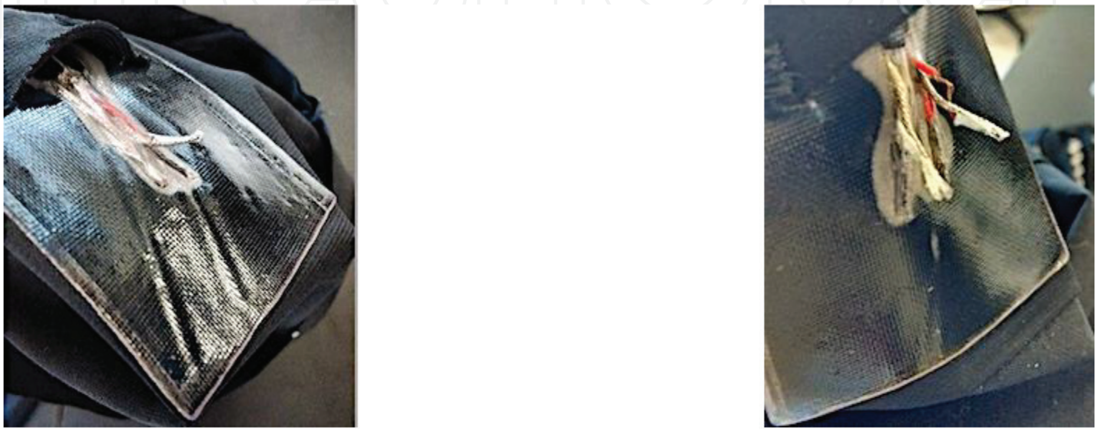

(a) (b)

Figure 5.
Soldered wires in a smart/e-textile product piercing through the wash-resistant polyurethane encapsulation layer.

(a) (b)

Figure 6.
Resistive heating blanket: (a) electronic control module with wiring for power supply; (b) connection between electronic module and the blanket (identified with the red box). The rigid connector is sewn to the blanket with a single row of stitches (shown in the inset).

Concerns also exist for non-textile rigid elements that are sewn to e-textiles for instance. The laundering process may damage them if they are fragile. They may also hit the flexible conductive interconnects when the textile is tumbled during washing or drying. **Figure 6** displays the example of a resistive heating blanket. The plastic connector between the non-washable electronic modules and the blanket could get damaged when exposed to the mechanical stresses and the elevated temperatures associated with laundering and tumble drying.

Another issue is associated with the tendency of some textile fibers to absorb water. As water swells the hydrophilic fibers, it influences their physical properties [40]. It can also reduce the flexural strength, modulus, strength, hardness, and fracture toughness at the textile fiber-polymer matrix interface [41]. Even hydrophobic fibers can transport moisture by capillary action. The water can reach the different e-textile components and damage them. Electronic modules and batteries are the most sensitive to water ingress, which can instantly and permanently damage them [42, 43]. Proper encapsulation is once again the solution when complete unplugging is not possible [37]. Alternatively, a water-free, air-based laundry system has been designed for smart garments [44].

Product lifetime is very important for consumers. A typical 100% cotton t-shirt provides serviceability for at least 20 washes [45]. Hence, the expectation of consumers is no less for smart textiles, especially due to their high price tag. OMsignal claimed that their smart t-shirt, designed for tracking heart and respiration rate, could undergo 50 wash cycles [46]. However, the company no longer exists. Karaguzel et al. designed a silver ink screen-printed nonwoven electro-textile circuit that could resist up to 25 wash cycles [47]. Cho et al. reported no change in conductivity of an rGO-coated meta-aramid woven fabrics after ten 6-min washing cycles at 40 °C using a Laundero-meter [30]. Similarly, intrinsic conductive polymers like PEDOT:PSS were used to exhaust-dye silk yarns and showed no change in electrical conductivity for up to 4 washing cycles [17]. Laminated and metallized textile yarn electrodes sustained successfully 20 domestic washing cycles according to EN ISO 6330 [39].

Researchers also used prolong washing to demonstrate the stability-to-laundering of smart textiles. Qui et al. observed a constant electrical output (voltage: ∼110 V, current: 2 μA) for their piezoelectric energy harvesting fabric based on biomechanical body movements after up to 2 h of continuous washing [18]; only a minor degradation in the output (voltage: ∼106 V, current: 1.9 μA) was recorded after 12 h of prolonged washing. The impact of powder detergent (containing conventional chlorine-based bleaching agents), liquid detergent, and sodium percarbonate (an unconventional stain remover based on oxygen bleach) was compared when testing the resistance of Ag-plated nylon electrodes to 30 washing cycles [42]. Detergents with bleaching agents were reported to be more damaging to the Ag-electrodes, as the bleaching agents oxidize the Ag layer, making the conductive layer vulnerable to mechanical rubs and progressive wash cycles. The researchers recommended using liquid detergents, free of any form of bleaching agents, for e-textiles. Recently, researchers from the University of Toronto and the University of Waterloo developed two different electrocardiogram (ECG) electrodes made of silver-coated and carbon-suffused nylon yarns [48]. Although silver-coated ECG electrodes resisted well up to 35 washes, the carbon yarns yielded a longer lifespan and maintained a reasonable signal quality for the ECG biosignals.

3.2 Safety

Safety is the biggest concern for e-textile users because of the fear of electric shocks from embedded electronics. Even though the embedded electronics are responsible for the smart behavior of e-textiles, the safety of the product should not be compromised by the presence of electronic components.

3.2.1 Electric shocks and shorts

Embedded electronics in e-textiles may suffer from short-circuits or mechanical failures, e.g. due to body sweat or ambient moisture, similarly to what is observed for electronic devices in marine environments [49]. Such malfunctioning can cause serious health hazards or fire accidents. For instance, a recall was issue for the Omni-Heat electric jackets of the company Columbia [50]. A manufacturing defect was detected in the heating component of the wrist cuff, which could create an electric short and lead to burn injuries. The electrical insulation of conductive components can be achieved by surrounding the conductive components with an electrically insulating layer, for instance through core spinning, using a tubular intarsia knitting, or by encapsulation in a water-resistant polymer for instance [51].

3.2.2 Exposure to high temperatures

Burns due to exposure to high temperatures is a serious safety concern for users of heating textiles. Skin temperature is around 34-35 °C although it differs slightly between different regions of the human body while the core temperature of the human body is maintained at around 37 °C [52, 53]. **Figure 7** illustrates the effect of exposure of the human skin to different temperatures [54–56]. While the burning pain threshold is at 43 °C, extended exposure of the skin to 45 °C can lead to 2nd and 3rd degree burns. Temperature overshooting or the malfunctioning of heating textiles could cause severe burn injuries, in particular for people with impaired sensations. For instance, a 26-year-old male patient with paraplegia suffered from a hip burn due to a heated car seat while driving a 2004 Jeep Cherokee for 30 minutes [57]. While the patient was unaware that the car seat was preprogrammed to a high setting ($\sim$41 °C), it was later revealed that the seat heater malfunctioned and exceeded 41 °C.

Similar unfortunate cases include a 42-year-old post-traumatic paraplegic patient in Germany who required several reconstructive surgeries as a result of burns caused by a heated car seat [58], a 54 old paraplegic patient driving a 1999 Chrysler Town & Country minivan who suffered from blisters in the rear and upper thigh [59], and a 50-year-old diabetic and paraplegic woman who suffered from a

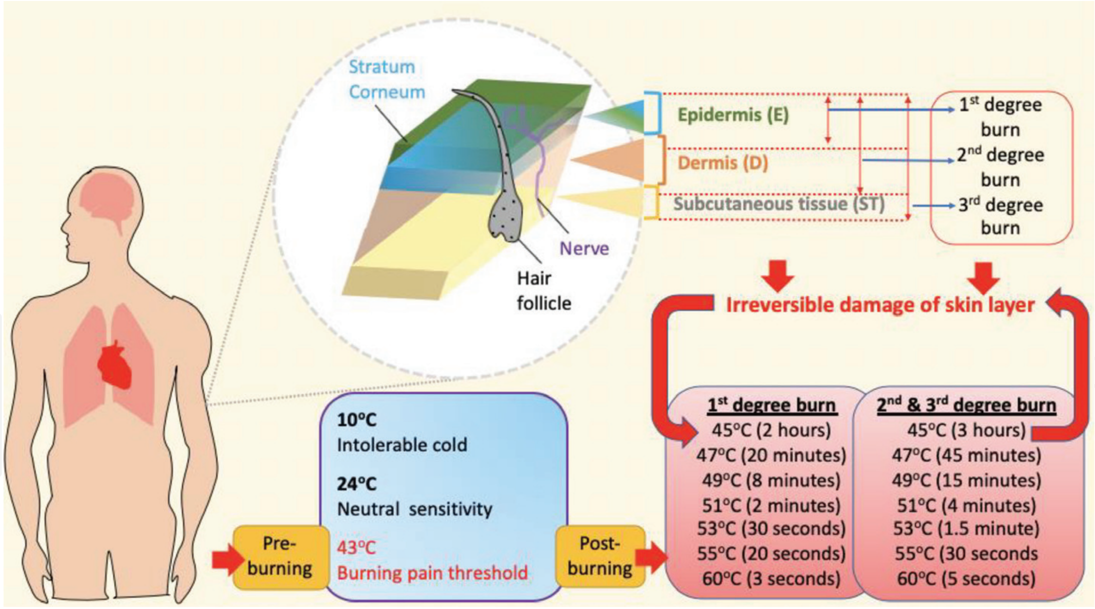
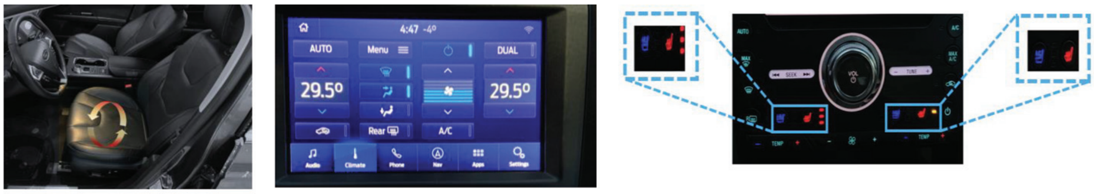


Figure 7.
Resistance of the human skin layers to low and elevated temperatures. Data retrieved from [54–56] (artwork by author).

partial-thickness burn on her medial buttocks [60]. Canada has cold winters and people use heated car seats during the winter; however, most of the heated seats do not display the temperature reached during operation. **Figure 8** displays the example of a North American 2020 full-sized sedan car with its heated car seats and different levels of heat settings; no indication of the actual temperature reached by the heated seats is available. As shown in **Figure 7,** an overheating at 50 °C may cause a 2nd or 3rd degree burn within 4 minutes. Beside medical patients, a temperature overshoot may also increase the risk of fire in the case of apparel articles with poor fire retardancy.

Similar smart heating technologies are also used by diabetic patients. Diabetic patients often suffer from nerve damages, termed as neuropathy, which involves sensory or motor impairment of small and large fibers of the body muscles [61]. The weakness of feet nerves is the most common type of diabetic neuropathy affects. Foot ulcers, sharp or burning pains in feet, and numbness of toes are other neuropathy symptoms [62]. To keep neuropathic pain under a manageable level, patients often undertake different physical therapies, including heat therapies by heating pads (**Figure 9a**) [63]. Since diabetic patients may suffer localized feet numbness and these heating pads are in direct contact with the skin, any temperature overshoot may cause serious skin burn injuries. Unfortunately, different heating textiles like heating blankets, mattress pads or throws (**Figure 9b**) are sold to consumers without proper instructions or clear indications. For instance, the heat regulator does not indicate the level of temperature it generates for its different heat settings (high, medium, low) (**Figures 9c**). Such an approach could harm sensitive skins as



(a) **(b)** **(c)**

Figure 8.
A full-sized sedan with its heated seat (a) and dashboard control modules with set temperatures (b). The car seat heat indicator is in tally marks (with no reference of actual temperature) (c).

Figure 9.
Examples of heating textile products. (a) a heating pad; (b) a 120 V (A.C.)/60 Hz/ 115 W electronic heating throw made of 100% polyester fiber; (c) heating control module without numerical indication of temperature levels for the three different heat settings (high, medium, low).

the heat tolerance level differs from person to person and patients with diabetes or paraplegia suffer from reduced or impaired sensitive body organs. Operation manuals also miss indications about the temperatures at the different heat settings and warnings about the dangers of prolonged heating times.

In addition, the accumulation of heat over time could also make the users of different electronic wearables feel uncomfortable [64]. Such issue is particularly critical in the case of joule heating textiles where it could lead to burns for the user or instance of fires. Due to the accumulation of heat in the textile over the successive heating/cooling cycles for instance, the temperature may keep on increasing even if the power input remains constant – a phenomenon which was marked in smart nylon gloves embedded with a polyurethane-copper nanowire (PU-CuNW) resistive heating element [22]. Kim et al. reported a temperature increase of 5 °C, from 85 °C to 90 °C, during a 10 h prolong heating period of the smart nylon gloves [22]. This temperature increase over time could potentially be associated with the ~7% increase they observed in the resistance of the conductive element of the PU-CuNW-nylon glove after the 10 h heating period. Thermal inertia may also lead to issues of overheating as the temperature experienced may exceed the set value, which can be associated with a phenomenon of overshooting.

3.2.3 Battery ignition and fire hazards

Recently, the US Homeland Defense and Security Information Analysis Center described the need for integrating multiple energy harvesting textiles on US military protective clothing [65]. Indeed, most wearable electronic systems need to be powered to be able to function. Strategies for textile-based energy harvesting are generally based on triboelectric (based on the friction between pieces of garments during body motion) [66], piezoelectric (from deformation during body motion [67], thermoelectric (using body heat) [68], and photovoltaic (from solar energy) power generation [69]. Recent scientific works also showed the potential of producing biochemical energy from body sweat using textile-based biofuel cell systems [70]. An overview of different energy harvesting textile platforms is illustrated in **Figure 10** for an application for dismounted soldiers.

In addition to energy harvesting, on-body batteries or supercapacitors are needed to store the energy from these energy harvesting fabrics and/or provide some power supply autonomy to the wearable clothing system [71]. However, these integrated batteries could suffer from battery ignition. One such incident was

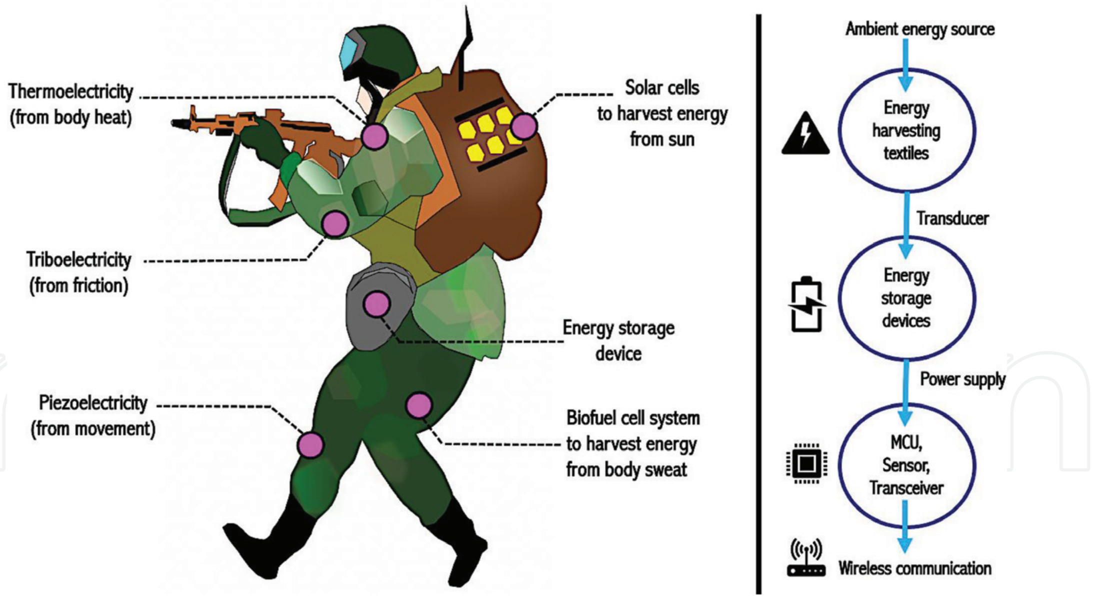


Figure 10.
An overview of energy harvesting systems for autonomous and self-charging protective military clothing with a simplified block diagram for wireless communication platform.

reported by the Department of Police in Arkansas (USA); a smart jacket caught on fire due to the ignition of its built-in battery [72]. Another example concerns the Omni-Heat electric jacket models of the company Columbia [50]. A recall resulted from defective batteries that could overheat and ignite the jacket. Similar incidents could have dramatic consequences, in particular in the military where an increasing number of e-textile systems are being encountered. For instance, in the US, the Future Force Warrior, Scorpion, and Land Warrior programs take advantage of copper and tinsel wire-based textile USB, radiating conductor, and electro-textile cables among others for improved flexibility and real-time information technology in military protective clothing systems [73].

3.2.4 Unstable connectivity

The reliance on smart textiles in case of emergencies is a growing trend for the biomedical, OH&S, and transportation industries. Any inconsistency or flaw in the interconnecting conductive tracks may render the emergency smart textiles dysfunctional, with potential dramatic consequences. Moreover, if the textile antennas or wireless communication system suffer any disruption in the communication protocol, it will make the user vulnerable to life-threatening situations. For example, Smart Enjoy Interact Light (SEIL) backpacks are manufactured for cyclists to avoid traffic accidents by displaying built-in LED lights or by expressing images in real-time [74]. The bag allows the user to show traffic signals like left/right, stop and emergency signs using a wireless controller. Any flaw in the conductive tracks or quality issues with PCBs (printed circuit boards) may disrupt the direct signal transduction, thereby putting the cyclists in danger. Other examples of smart textiles employed for health monitoring and disease prevention by early detection include the Vivago WristCare to monitor and transmit data on a person's health condition 24 hours a day – with benefits beyond the traditional push-button alarm; MARSIAN smart gloves to monitor and wirelessly transmit ANS (nonconscious) activities and real-time physiological (skin microcirculation, respiration rate, etc.) data; SenseWear body armband for measuring physiological parameters (motion, temperature, skin electrical conductance); VTAM biomedical t-shirt for teleassistance in medicine to monitor shock, fall, respiration, temperature, and location; and Vivometric's LifeShirt for ambulatory and plethysmographic respiration monitoring [75].

3.3 Efficiency

Thus far, the current chapter has discussed several aspects associated with the durability and safety of smart/e-textiles. Efficiency covers aspects such as the actuating performance against applied stimulus level or the quality of the biosignal detection in physiological applications. These aspects are also critical for the satisfaction of the smart/e-textile user.

3.3.1 Response time

Response time can be defined as the delay between the input, i.e., the activation by the stimulus, and the output of the smart/e-textiles. In the case of joule heating textiles, the response time can be determined from the time–temperature curves. Researchers have used different parameters to characterize the response time of heating textiles. For instance, R_{90} refers to the time required to reach 90% of the steady state temperature [24]. Xiao et al. reported a decrease in the R_{90} of a heating e-textile based on a carbon black nanoparticle-PU (polyurethane) composite film as the applied voltage was increased [76]. Another parameter used by researchers is the heat time constant (H_{TIME}) [25]. This is also known as response time constant (τ) [77]. The parameter τ characterizes the system's inertia [77]. It is defined as the time required to reach 63.2% of the maximum value, in this case the maximum temperature, according to the following equation (see Eq. (1)):

$$1 - e^{-1} = 1 - 0.3679 = 0.632 \text{ } or \text{ } 63.2\% \tag{1}$$

One solution developed by researchers to improve the reaction/response time of the carbon-based conductive materials is to take advantage of different metal fillers. For example, Ag nanowires were added to graphene oxide to prevent lattice defects during the reduction to rGO [78].

3.3.2 Power efficiency

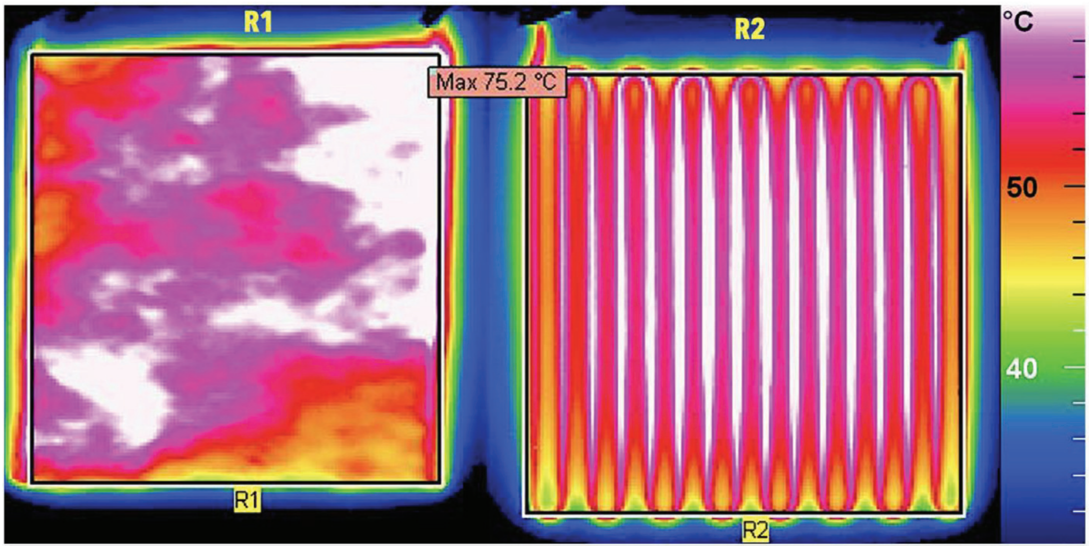
As many smart/e-textiles require power to operate, power efficiency is critical to maximize the wearability of the device. For joule heating textiles, researchers generally express the maximum temperature reached as a function of the applied power density to characterize the heating performance of the heating system, for example flexible graphene heaters for wearable electronics [79]. Work on thermoregulatory devices for cooling and heating applications, stretchable knit heating cotton gloves, and stretchable smart textile heaters based on copper nanowires have relied on heat flux density measurements to quantify the resistive heating performance [22, 24, 25, 80]. However, power efficiency is still a weakness for products currently on the market [5].

3.3.3 Uniformity of actuation

The uniformity of actuation is a critical parameter when considering heating textiles. For example, Hao et al. characterized the uniformity of the heating performance of a cotton woven fabric spray-coated with a graphene nanosheet conductive mixture by showing the temperature distribution from four different perspectives: (a) in the horizontal direction over a span of 4 cm (the length of the heater), (b) in the vertical direction over a span of 2 cm (the width of the heater), (c) observed from the top (sprayed face of the fabric), and (d) the bottom (non-sprayed face) [24]. They also compared the heat distribution in the flat and bent (180°) conditions. The 2D plane surface temperature distribution was uniform in both the horizontal and vertical directions during the 10–60s heating phase, which confirmed the uniform distribution of the conductive coating. However, a small temperature gradient was observed in the periphery of the heating fabric; the authors attributed it to heat loss by convection. The comparison between the sprayed and non-sprayed faces of the fabric showed a 3.5 °C difference, with the sprayed face exhibiting a temperature of 83.8 °C. No significant effect was noticed in the heat distribution when the flexible heater was bent by 180°. As another example of temperature distribution inhomogeneity, **Figure 11** displays the temperature measurement of two different heating fabrics: (i) a nonwoven heater (R1) and (ii) a fabric with heating wires (R2). Different patterns of spatial heat distribution are observed with both types of heating textile structures.

3.3.4 Repeatability/stability of the actuation level

A similar approach was undertaken by several researchers to evaluate the thermal stability of electrothermal textiles during repeated heating–cooling cycles of different amplitudes. The test would involve a series of stepwise or periodic or cyclic applied voltages, with the resulting temperature changes being recorded [76]. Some researchers also used specific actuation patterns. For example, Sun et al. characterized his segregated carbon Nanotube/thermoplastic polyurethane (s-CNT/TPU) heater with three different types of heating–cooling cyclic patterns [19]: (a) ten on/off periodic cycles at 6 V, (b) three cycles of 1.5–3-4.5-6 V step increase followed by an off period, and (c) five on/off periodic cycles at increasing then decreasing voltages (3–4.5-6-4.5-3 V). In general, two types of approaches have been observed among researchers investigating the efficiency of



Specimen	Mean	Min	Max	Std. Dev	Eps
R1	56.3°C	40.2°C	75.2°C	4.68°C	1.00
R2	54.8°C	36.8°C	68.3°C	4.84°C	1.00

Figure 11.
Comparison between the infrared temperature measurement of heating textiles using a conductive nonwoven structure (R1) and a conductive wire (R2).

wearable heaters: (a) cyclic heating–cooling tests at a fixed voltage, and (b) repetitions of the continuous profile of variable voltages.

3.3.5 Quality of biosignal measured

Smart/e-textiles for biomedical applications often incorporate textile sensors or electrodes. The efficiency of these devices depends on the quality of the biosignals recorded. Dry textile sensors suffer from high contact impedance between the skin and the electrodes [81]. This results in high signal distortion and level of noise, lowering the overall efficiency of the biomedical devices. To overcome this challenge, researchers have integrated a water reservoir to continuously dispense moisture vapor to a Ag/Ti-coated polyester yarn embroidered electrode and lower the motion artifacts [82]. However, this system still does not offer a long-term solution as the reservoir dries out after a few hours, disrupting the signal measurement protocols, and thereby, the product efficiency [83]. Ultimately, the efficiency in the linearity of the output signals will have to be improved by reducing the impact of temperature, mechanical vibrations, ambient relative humidity, and other atmospheric factors [84].

3.3.6 Negative impact of moisture

Moisture reduces the performance of all types of batteries, including textile batteries or batteries integrated into smart textiles [43]. Moisture may also cause chemical and physical interferences in the control module of e-textiles, reducing its efficiency before a total failure occurs [85]. Besides the possibility of electric shocks or complete signal loss from corrosion, marine e-textiles could also experience decreased efficiency when exposed to the salt of seawater. As soon as the saltwater propagates the localized corrosion process of textile electrodes or conductive interconnects, it could affect the overall signal quality, lowering the transduction efficiency [49].

3.4 Other issues reported and concerns with the use of smart textiles

3.4.1 Longevity of the power supply source

For the consumer satisfaction, the longevity of the system supplying power to the e-textile, either a battery or an energy harvesting component, is critical. Unfortunately, the same situation experienced in the mobile phone sector will potentially be observed with e-textiles, in particular with batteries and chargers. Components may even reach obsolescence faster due to the combination of specific life cycle factors associated with both the electronics and textile sectors [86].

3.4.2 Maintenance and repairs

Fault detection and maintenance are another critical aspect of e-textiles. Due to their seamless integration into smart textiles, routine maintenance of electronic components can be extremely difficult. Also, any attempt to repair of the defective components may permanently damage the smart textile products.

3.4.3 Electronic component and software upgrades

In an effort towards real-time data analytics, smart textiles provide a platform for portable computing for the consumers, for instance for biosignal and physiological data collection. Any difficulty to update the electronic components, firmware, networking protocols, and software could seriously jeopardize the lifetime of the e-textile product.

3.4.4 E-waste and legislation

E-waste already raises a major challenge. With e-textiles, the situation becomes even worse as they are more integrated, have a shorter life span, and will be more likely disposed of with their batteries [86]. In addition, if people own one cell phone, they have several tee shirts in their wardrobe. E-textiles may lead to contamination of other materials' recycling processes as well the increased release of toxic substances. Hence, proper standardization and appropriate regulations are needed for the safe disposal of this new generation of electronics.

4. Test methods: current state of knowledge & future needs

Several national and international standardization organizations have been working over the last 10 years towards the development of standards for smart/e-textiles. This includes the European Committee for Standardization (CEN) with technical committee CEN TC 248/WG 31, the International Electrotechnical Commission (IEC) with technical committee IEC TC 124, ASTM International with technical committee ASTM D13.50, the International Organization for Standardization with technical committee ISO/TC 38/WG 32, and the American Association of Textile Chemists & Colorists (AATCC) with technical committee AATCC RA111. Several of them have published and/or are working on the development of test methods for smart/e-textiles. A total of 18 published/in-development standard test methods are listed in **Table 2**. They are organized according to the classification shown in **Figure 1**. Four documents relative to terminology are also included in the table.

The distribution of existing sensor and actuator-based textile technologies, solutions, and products by category of input/output signal (**Figure 1**) can be compared with the standard test methods (published and in development) identified (**Figure 12**). While most of the test method development efforts for e-textiles are in the electrical category, which accounts for 55% of the total test methods published and in development, technologies, solutions, and products in the electrical category only represent 28% and 5% of the sensors and actuators, respectively. For their part, mechanical test standards only represent 11% of the total, whereas technologies, solutions, and products in the mechanical category comprise 59% of the sensor-based smart/e-textiles. Also, very few standard test methods exist for thermal, optical and physical environmental aspects of e-textiles, while commercial products in these categories account for a large part of products/technologies in the market. No standards are available yet for power/energy harvesting and chemical/biological e-textiles, while some related products already exist on the market. This situation has led several researchers and research institutions to develop their own test methods [107]. It must be mentioned that test methods characterizing the electrical function were included in the electrical category while they may also, in a certain extent, apply to other categories of smart/e-textiles.

Based on the number of commercial e-textile products currently available and issues reported in terms of safety, efficiency, and durability, there is thus a critical need for test methods for thermal applications, as well as to a lesser degree, for energy (power) harvesting and chemical and biological applications. For this purpose, a trifactor model of performance assessment is illustrated in **Figure 13**.

Test method	Document
Electrical (Total of 10 test method standards, 1 published and 9 in development)	
ASTM WK61479- Durability of textile electrodes exposed to perspiration (in development)	[87]
ASTM WK61480- Durability of textile electrodes after laundering (in development)	[88]
AATCC RA111(a)- Electrical resistance of electronically integrated textiles (in development)*	[89]
AATCC RA111(b)- Electrical resistance changes after home laundering (in development)*	[90]
CEN EN 16812:2016- Linear electrical resistance of conductive tracks*	[91]
IEC 63203–204-1- Washable durability for leisure and sportswear e-textile system (in development)*	[92]
IEC 63203–201-3- Electrical resistance of conductive textiles under simulated microclimate (in development)*	[93]
IEC 63203–250-1- Snap button connectors (in development)*	[94]
IEC 63203–201-1- Basic properties of conductive yarns (in development)*	[95]
IEC 63203–201-2- Basic properties of conductive fabric and insulation materials (in development)*	[96]
Thermal (Total of 4 test standards, 1 published and 3 in development)	
CEN EN 16806–1:2016- PCM - Heat storage and release capacity	[97]
CEN EN 16806–2 PCM- Heat transfer using a dynamic method (in development)	[97]
CEN EN 16806–3 PCM- Determination of the heat transfer between the user and the product (in development)	[97]
IEC 63203–406-1- Measuring skin contact temperature (in development)	[98]
Mechanical (Total of 2 test standards in development)	
IEC 63203–401-1 - Stretchable resistive strain sensor (in development)	[99]
IEC 63203–402-1 – Finger movements in glove-type motion sensors (in development)	[100]
Physical environment (Total of 1 test standard in development)	
IEC 63203–402-2 - Fitness wearables – step counting (in development)	[101]
Optical (Total of 1 test standard in development)	
IEC 63203–301-1 - Electrochromic films for wearable equipment (in development)	[102]
Others (Total of 4 test standards, 2 published and 2 in development)	
ASTM D8248–19- Standard terminology for smart textiles	[103]
ASTM WK61478- New terminology for smart textiles (in development)	[104]
CEN 16298 - Definitions, categorization, applications and standardization needs	[105]
IEC 63203–101-1 – Terminology (in development)	[106]

**Also applies to other categories of products/technologies.*

Table 2.
Standards (existing and in development) test methods for smart textiles.

The product assessment should also take into account the product features, longevity, benefits/cost ratio, and the user experience.

Applying this trifactor model, we have identified the need for more than thirty standard test methods in the specific case of thermal e-textile products (**Tables 3**–**5**). They include a full-sleeve resistive heating jacket, battery-powered resistive heating boots, resistive heating car seats, battery-powered resistive heating gloves, a

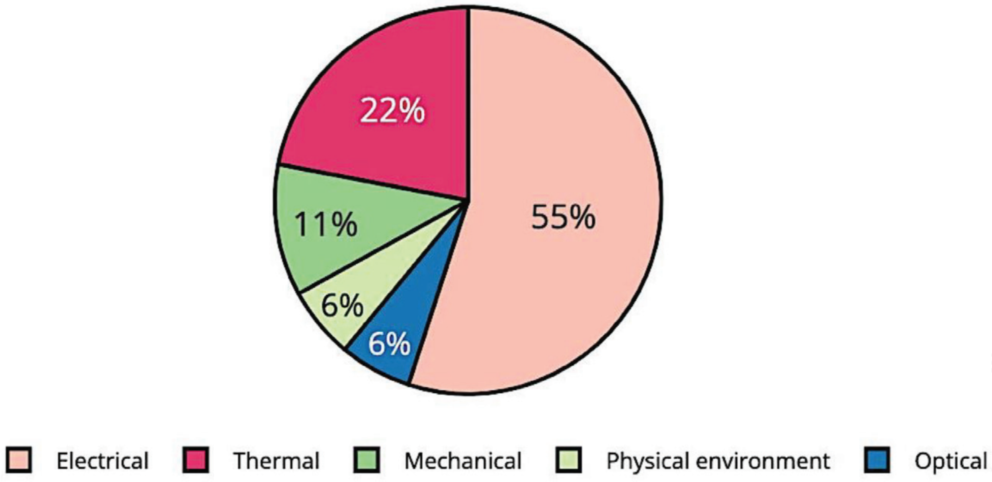


Figure 12.
Existing/in-development standardized test methods for smart textiles as of December 2020.

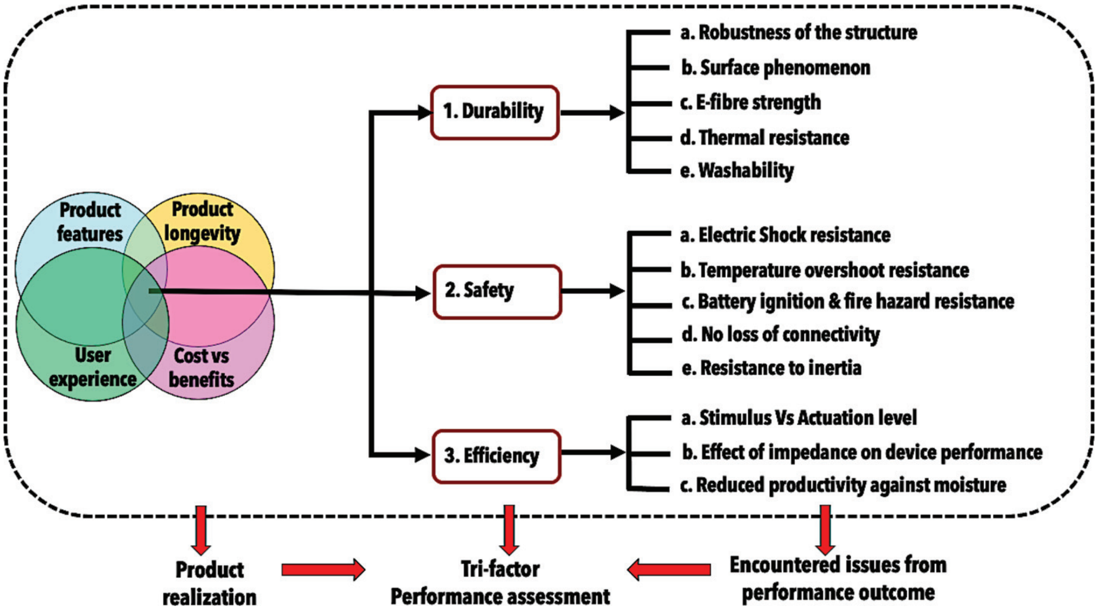


Figure 13.
Tri-factor framework for assessing the performance of smart/e-textiles.

Performance evaluation	Applicable standards
Efficiency of the overall functional/protective clothing system	Not available
Efficiency of the heat transfer system between textile and user (at the component level)	Not available
Efficiency of the induction-charging system	Not available

Table 3.
Test methods needed to evaluate the efficiency of smart/e-textiles.

reflective heating jacket, an air-exchange heating face mask, a cooling vest using water circulation and a Peltier module, and a thermo-regulated jacket with phase change materials. The few standard test methods already published and in development are also included in the tables when relevant: in several cases, the standard would not apply to the case of thermal e-textiles used as an example here. In the

Performance evaluation	Applicable standards
Efficiency of protection against shorts or open circuit, leading to shocks or fire hazards	IEC 63203–201-2 is in development, but it may not apply to high resistance conductive fabrics used for antistatic or heater purposes
Efficiency of controls (i.e., power limit) to avoid over-heating, leading to skin burn or damage	IEC 63203–406-1 ED1 is in development but it appears to be limited to wearable electronic devices
Impact of prolonged heating exposure on the skin and the surrounding environment	Not available
Overshooting of temperature difference between set temperature and experienced temperature by the skin	Not available

Table 4.
Test methods needed to evaluate the safety of smart/e-textiles (include test methods published and in development when relevant).

Performance evaluation	Applicable standards
Electrical resistance of the heater/resistive material to cleaning (washing/ laundering, dry-cleaning, drying)[a,d]	ASTM WK61480 (draft) AATCC RA11 (draft) IEC PN 63203–201-2 (draft)
Electrical resistance of the heating element to exposure of perspiration (from different parts of the body)[a,b,d]	ASTM WK61479 (draft) IEC PN 63203–201-2 (draft)
Electrical resistance of the heating element when subjected to mechanical stresses (tension /compression/ bending / fatigue/ abrasion/cutting /tearing / bodyweight)[a,b,c,d]	IEC PN 63203–201-2 is in development, but it does not appear to cover the aspects of abrasion, cutting, tearing, and fatigue
Electrical resistance of conductive parts to steaming or ironing (after laundering)[a]	Not available
Electrical resistance of the heating element to extreme weather conditions (e.g., rain and snow)[a,b,c,d]	Not available
Electrical resistance of the heating elements after exposure to severe use conditions (hot/cold/high humidity)[a,b,c,d]	Not available
Electrical resistance of the heating elements after exposure to different kinds of liquid (water, coffee, soft drinks)[c,d]	Not available
Electrical resistance of conductive track to cleaning[a,b,c,d]	ASTM WK61480 (draft) AATCC RA11 (draft) IEC PN 63203–201-2 (draft)
Electrical resistance of fasteners (e.g., switch, snaps, power supply) to cleaning[a]	Not available
Electrical resistance of fasteners to power supply to repetitive connection/disconnection for cleaning, i.e., fatigue[a,d]	Not available
Electrical resistance of fasteners to steaming/ironing[a]	Not available
Electrical resistance of fasteners to the power supply to exposure of perspiration (e.g., corrosion)[a]	Not available
Resistance of reflective thermal heating pattern to cleaning (washing/ laundering, dry-cleaning, drying)[e]	Not available
Resistance of reflective thermal heating pattern to body abrasion [e]	Not available

Performance evaluation	Applicable standards
Resistance of reflective thermal heating pattern to perspiration[e]	Not available
Preservation of thermal heat reflection of liner fabric over time i.e., aging behavior[e]	Not available
Resistance of antimicrobial property of ventilator to cleaning (washing/ laundering/ dry-cleaning/ drying)[f]	Not available
Resistance of structural integrity of the ventilator against external compression and abrasion[f]	Not available
Efficiency of the heat recovery of the ventilation system from the exhaled breath[f]	Not available
Efficiency of the transformation mechanism of cold inhaled air into warm air inside the ventilator[f]	Not available
Resistance of structural integrity of the bladder/reservoir to compression and abrasion (with zipper track while detaching)[g]	Not available
Heat storage and release capacity of phase change material (PCM)[h]	CEN EN 16806–1 (Part- 1)
Resistance of PCM and coatings (many contain binders) to washing/ laundering/ dry-cleaning/ drying[h]	Not available
Resistance of PCM and coatings to abrasion[h]	Not available
Resistance of PCM and coatings to perspiration[h]	Not available
Determination of cooling or heat transfer of the PCM (coated or portable packs) technology[h]	CEN EN 16806–1 (Part- 2)
Resistance of PCM and coating to steaming and ironing[h]	Not available
Efficiency of PCM (coated or portable packs) technology over the course of the time i.e., aging behavior (weather conditions)[h]	Not available
Efficiency of PCM (coated or portable packs) technology to fatigue[h]	Not available

[a] *Resistive heating jacket.*
[b] *Resistive heating boot.*
[c] *Resistive heating car seat.*
[d] *Resistive heating gloves.*
[e] *Reflective heating jacket.*
[f] *Air-exchange heating face mask.*
[g] *Cooling vest using water circulation and a Peltier module.*
[h] *Thermo-regulated jacket with phase change material.*

Table 5.
Test methods needed to evaluate the durability of smart/e-textiles (include test methods published and in development when relevant).

case of the durability assessment, the analysis considered the specificities of the application corresponding to the product under consideration.

5. Conclusion

After a brief overview of smart/e-textile products and major barriers to market entry, this chapter discussed different issues reported as well as foreseeable challenges that may result in injuries for instance, with electric shocks, skin burns and fires. Aspects related to the user's satisfaction, for instance in terms of the product longevity and the ability to maintain/repair it, were also covered. In particular, different conditions such as biomechanical stresses applied during use, ambient moisture, and laundering may reduce the life expectancy of the smart textile due to a damage of the conductive interconnects or a reduced actuation, for instance. As the world moves towards an increased adoption of smart e-textiles, such unwanted outcomes can put the lives of healthcare patients, first responders, and soldiers, for instance, at risk.

Due to the lack of dedicated standard test methods, manufacturers of e-textiles are limited in their attempt to control the quality of their products; as a result, they are unable to scale up and have their innovative e-textile technologies and products reach their full potential. It is clear that the issues reported in terms of safety, durability, and efficiency of e-textiles can be mitigated and eliminated through appropriate quality control using standard test methods. Currently, only 18 standard test methods published and in development by CEN, IEC, ASTM, and AATCC technical committees relevant to smart/e-textiles were identified. In some categories of e-textiles, e.g., thermal, chemical, biological, and energy harvesting, few or no test methods exist while several products are already on the market.

Using a trifactor model of performance assessment based on safety, efficiency, and durability, more than 30 standard test methods were identified for thermal e-textiles by considering a series of existing technologies/products: a full-sleeve resistive heating jacket, battery-powered resistive heating boots, resistive heating car seats, battery-powered resistive heating gloves, a reflective heating jacket, an air-exchange heating face mask, a cooling vest using water circulation and a Peltier module, and a thermo-regulated jacket with phase change materials. The development of such product-oriented test methods and their adoption by the manufacturing industries, will facilitate the design process towards a safer, more efficient, and durable smart/e-textile world. Adopting a collaborative and multidisciplinary approach, involving textile, materials, biomedical, and electrical engineers as well as relevant national and international standardization technical committees in textiles and electronics, is key to achieving this.

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