Applications of smart textiles in occupational health and safety

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Abstract. Smart textiles can detect, react, and adapt to various stimuli; they offer promising perspectives in occupation health and safety (OH&S). The objective of this study was to identify technologies, solutions, and products based on smart textiles and flexible materials that could have an application in OH&S and provide a response to some of the current needs. The collection of information included three aspects: 1) technologies, solutions, and products involving smart textiles and flexible materials found in the literature over the period 2000-2016; 2) issues in OH&S associated with traditional textiles and flexible materials; and 3) current or foreseeable problems associated with the use of smart textiles and flexible materials in OH&S. Issues with traditional textiles and flexible materials in OH&S were cross-matched with technologies, solutions and products relevant to smart textiles and flexible materials. This allowed us to propose short, mid, and long-term developments that could provide a response to some of the current needs in OH&S. The analysis shows that smart textiles and flexible materials offer a promising response to current challenges observed with PPE used in OH&S. With manufacturing and R&D capabilities available in various countries, the feasibility of development of these solutions is very high.

1. Introduction

While the use of electricity in illuminating and animated garments and accessories can be traced back to the end of the 19th century [1], the development of smart textiles only really began in the mid 80’s with the invention of wearable computers [2] and manufacturing equipment allowing the incorporation of optic fibers into textiles [3]. The first commercial products incorporating smart textiles reached the market in the years 2000 with applications mainly targeting vital sign monitoring [4].

Smart textiles can detect, react, and adapt to various stimuli, e.g., electrical, magnetic, thermal, mechanical, chemical, and optical [5]. These three levels of functionalities define the three categories of smart materials [6]: passive with only sensing capability; active with both sensor and actuator functionalities; and ultra-intelligent, i.e. able to sense, react and adapt to stimuli. Smart textiles offer promising perspectives in occupation health and safety (OH&S), with embedded geolocation, monitoring of people’s physiological condition, heating and cooling, wireless communication, and energy harvesting for instance.

Three generations of smart textiles can be identified [6]. In the first generation, of which examples can already be seen on the market, active functions are added at the final product assembly stage. For the second generation, smart components are embedded in the textile during its production. The third
generation of smart textiles, on which researchers are still working and which is not expected to reach the market before 10 years, will hold the active parts within their fibers and yarns; they will be integrated at the extrusion or spinning stages.

The objective of this study was to identify technologies, solutions, and products based on smart textiles and flexible materials that could have an application in OH&S and provide a response to some of the current needs in OH&S. The research also involved determining current or foreseeable problems associated with the use of smart textiles and flexible materials in OH&S.

2. Methods
The collection of information involved three aspects. First, we analyzed the technical and scientific literature to identify technologies, solutions, and products involving smart textiles and flexible materials over the period 2000-2016. In total, more than 500 papers in journals and conference proceedings, patents, articles in textile news bulletins, and technical datasheets on manufacturer and distributor websites relevant to the subject were identified. The information gathered included a short description of the technology, solution or product; the nature of the stimulus; the type of system (device or material); the level of technology readiness; existing and suggested applications; and the limitations indicated. A list of 184 companies involved in smart textiles was also prepared with some information including the type of product (clothing; accessories; component; software) and a description of the technology; this list comprises more than 60 Canadian manufacturers.

The second aspect investigated dealt with the identification of issues in OH&S associated with traditional textiles and flexible materials, i.e. whose properties and performance are fixed and cannot adapt to the conditions encountered. Information was obtained from prevention counsellors in various professional activity sectors in Quebec, Canada (automotive; construction; farming; fisheries; food transformation; foundries; manufacturing of transportation equipment and machines; metal, electric, apparel & printing; mining; municipal affairs; provincial administration; pulp and paper; social affairs; and textile & hosiery). Interviews were also conducted with OH&S researchers, sales representatives of companies manufacturing personal protective equipment (PPE) used in OH&S, product development managers at protective textile manufacturers, and procurement officers in organizations using PPE. For each issue put forward, information was obtained about the activity sector(s) concerned, the category and number of workers affected, the solution currently implemented if any, and the presence of other constraints (e.g. related to cost or conditions of the work environment).

All these resource-persons were also questioned about the third aspect of the study related to current or foreseeable problems associated with the use of smart textiles and flexible materials in OH&S. They were asked if they had been in contact or aware of products used in OH&S that contained smart textiles and flexible materials; if positive, a short description of the product, activity sector and use conditions, and problems identified were noted. Input from experts at the Canadian Department of National Defence was obtained too. Finally, a brainstorming session with the research team was organized to complete the list of current or foreseeable problems associated with the use of smart textiles and flexible materials in OH&S based on their analysis of the relevant scientific and technical literature.

3. Results and discussion

3.1. Technologies, solutions, and products based on smart textiles and flexible materials that could have an application in OH&S
Three main categories of technologies, solutions, and products relevant to smart textiles and flexible materials were identified: sensors, actuators, and materials/components. A complete list of the technologies, solutions, and products identified in the study can be found in [7].

Examples of textile-based sensors include temperature, heat flux, pressure, strain, gas, pH, chemical, humidity, obstacle, proximity and location sensors as well as textile electrodes. Their input signal or stimulus is the main characteristic of interest. Sensors responding to a mechanical and electrical stimulus represent 59 and 23%, respectively, of the sensor-type technologies, solutions, and products identified
A few sensor-type products designed for OH&S applications were identified, for instance a smart shirt collecting vital signs that was used by Canadian astronaut David Saint-Jacques during his mission aboard the International Space Station in 2018-19 [8]; protective gloves that change color when sensing toxic chemicals in the air [9]; smart trousers that detect when a chain saw gets too close and switch it off [10]; an instrumented glove that captures the motion of the user’s hand and fingers and can be used for the collection of ergonomic ground data in the workplace [11]; and a lifeline system for firefighters that stores tactical information such as location of doors and victims [12].

Actuators can be defined by their output signal. They include heating fibers, antibacterial fabrics, textile displays, self-cleaning surfaces, a self-actuated defibrillator integrated in a garment, and photovoltaic fibers. Thermal, optical and power actuators each account for about a quarter of the actuator-type technologies, solutions, and products identified (Figure 1). A few actuator-type products designed for OH&S applications were also identified. They include a chemical protective garment that provides on-demand cooling [13]; antibacterial medical protective garments that can be recharged by washing with chlorine bleach [14]; surgical gowns with self-adjustable breathability [15]; and an active vest designed for caregivers that prevents incorrect movements when lifting heavy loads [16].

Finally, materials and components relevant to smart textiles and flexible materials comprise various polymers, carbon-based materials, metals, inks, connectors, and antennas.

**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).

### 3.2. Issues in OH&S associated with traditional textiles and flexible materials

The same type of classification was used to analyze the information obtained in terms of issues in OH&S associated with traditional textiles and flexible materials. The complete list of issues mentioned by the resource-persons interviewed can be found in [7].

Sensors represent about 25% of the issues reported. Among them, 31% involve a stimulus related to the physical environment (Figure 2). Issues associated with a mechanical, electrical or chemical stimulus each account for 20% of the sensor-type issues. Needs include for instance chemical sensors embedded in lab coats to detect chemical exposures; temperature sensors monitoring the conditions inside the protective clothing to avoid heat stress; safety harnesses equipped with mechanical sensors to alert other workers in case of a fall from height; and vital sign sensors combined with embedded geolocation systems for people working alone in remote locations or in confined environments.

In the case of actuators, the most frequent needs reported involve a thermal output (32%) and a mechanical output (31%) (Figure 2). Examples of actuator-type needs include thermoregulating systems for highly protective or fully encapsulating garments; protective gloves whose level of protection and dexterity vary based on the task; protective gloves and clothing which neutralize the biological agent before it reaches the skin in case of cut or needle puncture; and protective garments increasing their breathability in case of high intensity activity or when going from a cold to a warm area.
3.3. Current or foreseeable problems associated with the use of smart textiles and flexible materials in OH&S

A series of current or foreseeable problems associated with the use of smart textiles and flexible materials in OH&S have been identified and grouped into eight categories [7]:

- **Lack of maturity of the technologies associated with smart textiles.** Current systems still need improvements in terms of durability (resistance to sweat, repeated launderings, wear, etc.), reliability (accuracy, repeatability, and reproducibility) and energy efficiency. In addition, energy harvesting systems are still far from reaching the market. Thermal signature is also a challenge for military applications.

- **Potential negative health and safety outcomes.** Concerns have been raised both in terms of manufacturing, with particles of all sizes entering or generated by the process, as well as use. This includes the potential toxicity of nanoparticles and metals, effects of electromagnetic fields, accidental electric shock, and inability to activate the emergency shut-off device in case of a malfunctioning smart protective glove. An important point also regards ethics, with the question of information management and personal data safety.

- **Potential interference and incompatibility issues.** Responses are needed regarding the risk of interference of wearable electronics with communication systems and other electronic systems such as pacemakers. In addition, the presence of electrically conductive components in PPE is not compatible with requirements for electric shock and electrical arc protection. Internal and external environmental conditions such as profuse sweat and rain may also interfere with smart textile proper operation.

- **Gap in the relevant knowledge, standards, and test methods.** Needs include an in-depth understanding of new product operation and the generation of data about device safety and behavior over time for instance. The smart textile industry also misses strategies for managing improper use. Finally, the lack of appropriate standard test methods and regulatory framework may generate risks for the user. This delay in background research is often observed with new technologies with a strong commercial growth potential that benefit from large investments.

- **Issues with accessibility.** The accessibility of products based on smart textiles and flexible materials in OH&S is limited by the cost of the product itself, which can be traced in some instances to the high price of the functionalizing component/material, as well as of accessories necessary for its operation, for instance chip-reading gates for tracking the use of safety harnesses.

- **Issues with use and care.** A major limitation to smart textile use is related to batteries: their weight and bulkiness as well as the charging process. Care is also a huge challenge, especially for protective
clothing. To be relevant for use in OH&S, smart textiles have to resist wear and severe environmental conditions such as high moisture for rain gear and high temperature for firefighter protective clothing.

- **Lack of validation of the real value for the user.** The adoption of smart textiles and flexible materials in OH&S is conditional to demonstrating that benefits outweigh additional costs and potential negative side effects. This analysis should involve experts in all aspects relevant to the smart product application.

- **Challenges related to end of life.** Smart textiles present the same challenges as traditional e-waste [17]: their amount is increasing worldwide and they contain problematic as well as valuable substances. They also raise additional issues due to the fact that they are more integrated and in larger number, have a shorter life span, and are often disposed of with their batteries. In particular, it is critical to ensure that the incineration of domestic waste performed by some countries to reduce landfilling does not create new hazards for health and the environment because of the presence of smart textiles.

3.4. Short, mid, and long-term developments proposed to respond to current needs in OH&S using smart textiles and flexible materials

The issues in OH&S reported with traditional textiles and flexible materials were cross-matched with the technologies, solutions and products relevant to smart textiles and flexible materials identified to propose short, mid, and long-term developments that could provide a response to some of the current needs in OH&S.

For instance, a short-term response to the need for thermoregulation in protective garments could rely on commercial products for athletes to warn workers when their vital signs point towards thermal stress onset and on existing cooling/heating systems with an external power source. In the mid-term, existing technologies such as phase change materials could be integrated as removable components in the garment. Ultimately, the solution would be completely embedded in the fabric, yarns or fibers; allow long-term thermoregulation; and be resistant to extreme work conditions, wear, and laundering.

The detection of contaminants could take advantage of existing technologies such as chemical-sensitive dyes in the short-term. In a next phase, textiles would be developed to detect and filter toxic contaminants. Ultimately, they would neutralize them.

In terms of musculoskeletal support, short-term solutions could rely on commercially available customized exoskeletons. Mid-term developments would use active technologies such as electrostimulation and shape memory textiles. In the long run, textiles will adjust their shape and stiffness depending on the mechanical constraints.

The complete list of development projects proposed for smart textiles and flexible materials in OH&S can be found in [7].

4. Conclusion

The analysis conducted as part of this study shows that smart textiles and flexible materials offer a promising response to current challenges observed with protective clothing and PPE used in OH&S. A series of short, mid, and long-term developments are proposed based on a cross analysis between issues in OH&S reported with traditional textiles and flexible materials and technologies, solutions, and products relevant to smart textiles and flexible materials identified in the technical and scientific literature.

With manufacturing and R&D capabilities available in various countries, including more than 60 companies and several research groups involved in smart textiles and flexible materials in Canada, the feasibility of the corresponding development projects is very high. This is especially true for short and mid-term proposals as they rely primarily on the optimization of existing products and technologies to improve their reliability, durability, and ease of operation.

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