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Challenges in producing smart clothing for professional wear: a scoping review

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Abstract

The purpose of this thesis was to analyze the challenges preventing manufacturers to produce smart clothing for professional wear on large scale. To answer this main research question, three research sub questions have been defined: what the main components of smart clothing are, what manufacturing techniques make traditional textiles smart, and which smart clothing applications for professional wear are currently on the market or in final prototype stage.

This thesis was produced as a scoping review. The process for collecting and analyzing data was done following the protocols described in literature. Literature searches were conducted in the following databases: PubMed, IEEE Xplore, Google Scholar, Theseus and ResearchGate. Only freely accessible studies published in English between 2015-2020 have been included. The search process was done systematically, and after content analysis and critical appraisal, 16 studies were withheld for further analysis in this scoping review. The 53 commercial smart clothing applications mentioned in these 16 studies were furthered analyzed using the same databases and general Google search. Ten commercial applications were withheld for further analysis in this scoping review.

The results showed that despite technological development and research, the technologies used for smart clothing are still not mature enough. But even more than that, the biggest challenges lay in the lack of standards, regulations, and cultural adaptability of smart clothing on the work floor. Manufacturers do not want to invest in production lines if there are no guarantees that employees and employers will use the smart clothing on the work floor. For this, privacy issues need to be dealt with and testing standards and legislation need to be put in place.

Key words:
Smart clothing, e-textiles, smart workwear, smart personal protective equipment, smart PPE

FOREWORD

Upon researching different topics for my thesis, I was looking for something in the field of wearables because I have a strong interest in these products. Exploratory search showed that the domain of smart watches has been widely researched and analyzed already, but one domain within the field of wearables seemed less explored: smart clothing. I was immediately fascinated by this topic. Further research, and guidance from my mentor D.Sc. Elina Ilén took me in the direction of smart clothing for professional wear. It is much less explored than the smart clothing for fitness or fashion.

The thesis has brought me many insights in this domain. Despite the extra security and protection it offers workers, I was surprised to see that very few smart clothing applications are in use today. I will keep following the trend in this domain and it will be interesting to see at which point the smart clothing will appear on the market for purchase.

I would like to thank D.Sc. Elina Ilén, CEO at Planno Oy and Post-Doc Researcher at Aalto University, to be my mentor during the writing of my thesis. Her insights in the field have been very valuable. Also, my supervisors Sari Merilampi and Merja Sallinen, both professors at the Satakunta University of Applied Sciences, have been extremely important in guiding me during the writing process of this scoping review. I would like to thank them both.

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LIST OF SYMBOLS AND TERMS

AI	Artificial intelligence
AoA	Angle of Arrival
AR	Augmented Reality
ASTM	American Society for Testing and Materials
BAN	Body Area Network
BLE	Bluetooth Low Energy
CCD	Charge-Coupled Device
CMO	Complimentary Metal-Oxide
CPU	Central Processing Units
ECG	Electrocardiogram
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMC	Electromagnetic compatibility
EMF	Electromagnetic fields
FGPAs	Field-Programmable Gate Arrays
GIS	Geographical Information System
HR	Heart Rate
IIOT	Industrial Internet of Things
INAIL	National Institute for Insurance against Accidents at Work
KAN	German Commission for Occupational Health and Safety and Standardization
LAN	Local Area Network
LCD	Liquid-crystal display
LED	Light-Emitting Diodes
MSD	Musculoskeletal Disorders
NFC	Near Field Communication
OH&S	Occupation health & safety
OLED	Organic light-emitting diode
OSH	Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PAN	Personal Area Network
PCB	Printed Circuit Board
PPE	Personal Protective Equipment
PSIM	Physical Security Information Management
RAS	Relative Aerobic Strain
RFID	Radio-frequency identification
RPE	Respiratory Protective Equipment
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator

SWM	Solid Waste Management
TDoA	Time Difference of Arrival
TEB	Thoracic Electrical Bio-Impedance
ToA	Time of Arrival
UWB	Ultra-Wide Band
VOC	Volatile organic compounds
WAN	Wide Area Network
WBAN	Wearable Body Area Network
WMSD	Work-related musculoskeletal disorders
WPAN	Wireless Personal Area Network

1 INTRODUCTION

Wearable technology has gone through a huge growth in the past 20 years. This is especially thanks to the increasing mobile phone usage and the rapid development of Internet of Things. People wear devices that can track physiological functions and give insights to their workouts, sleeping pattern or stress levels. Many attempts have been made to integrate electronics into clothing, and as such make the clothing a smart wearable as well. (Ju & Lee, 2020, p.1.) However, while the wearables of (hard) accessories and devices such as earbuds and watches have saturated the market, there are still few smart clothing applications on the market, even though there has been a considerable amount of research done already in the domain. (Wu & Li, 2019, p. 1).

The objective of this scoping review is to analyze smart clothing applications for professional wear currently on the market and identify the challenges that hinder production on large scale.

It is important to make a distinction between conventional textiles, the ones we know in everyday life, and smart textiles. Depending on the materials used, conventional textiles are designed to provide certain functionalities such as e.g., warmth, breathability, being wind- or waterproof. Smart textiles can interpret data generated by triggers coming from their environment and react according to it (Ismar et al., 2020, p. 1).

Although often used intertwined, it is also important to mention the difference between smart textiles and e-textiles. According to the “Standard Terminology for Smart Textiles” released on July 29, 2019 by The American Society for Testing and Materials (ASTM), a smart textile doesn’t necessarily have an electrical function integrated, while e-textiles are always made of electronic components (ASTM International, 2019). This research will focus on e-textiles; textiles and clothing that are fabricated using technology and electronics. As e-textiles is a subcategory of smart textiles, the term “smart” will be used throughout the research report, always referring to the e-textiles - except when specifically mentioned otherwise.

2 BACKGROUND

As this literature review focuses on smart clothing for professional wear, it is important to understand some concepts that are used in this industry. This chapter will first discuss the evolution that has happened within smart clothing. After that, some basic concepts that frequently appear in the studies, will be explained: Industry 4.0, Industrial Internet of Things (IIOT) and Smart Personal Protective Equipment (PPE).

2.1 Evolution of smart clothing

Wu & Li (2019, pp. 6-9) stated that smart textiles and apparel have evolved through different degrees of intelligence but also the degrees of integration and self-efficiency of smart textiles have gone through an evolution (Figure 1).

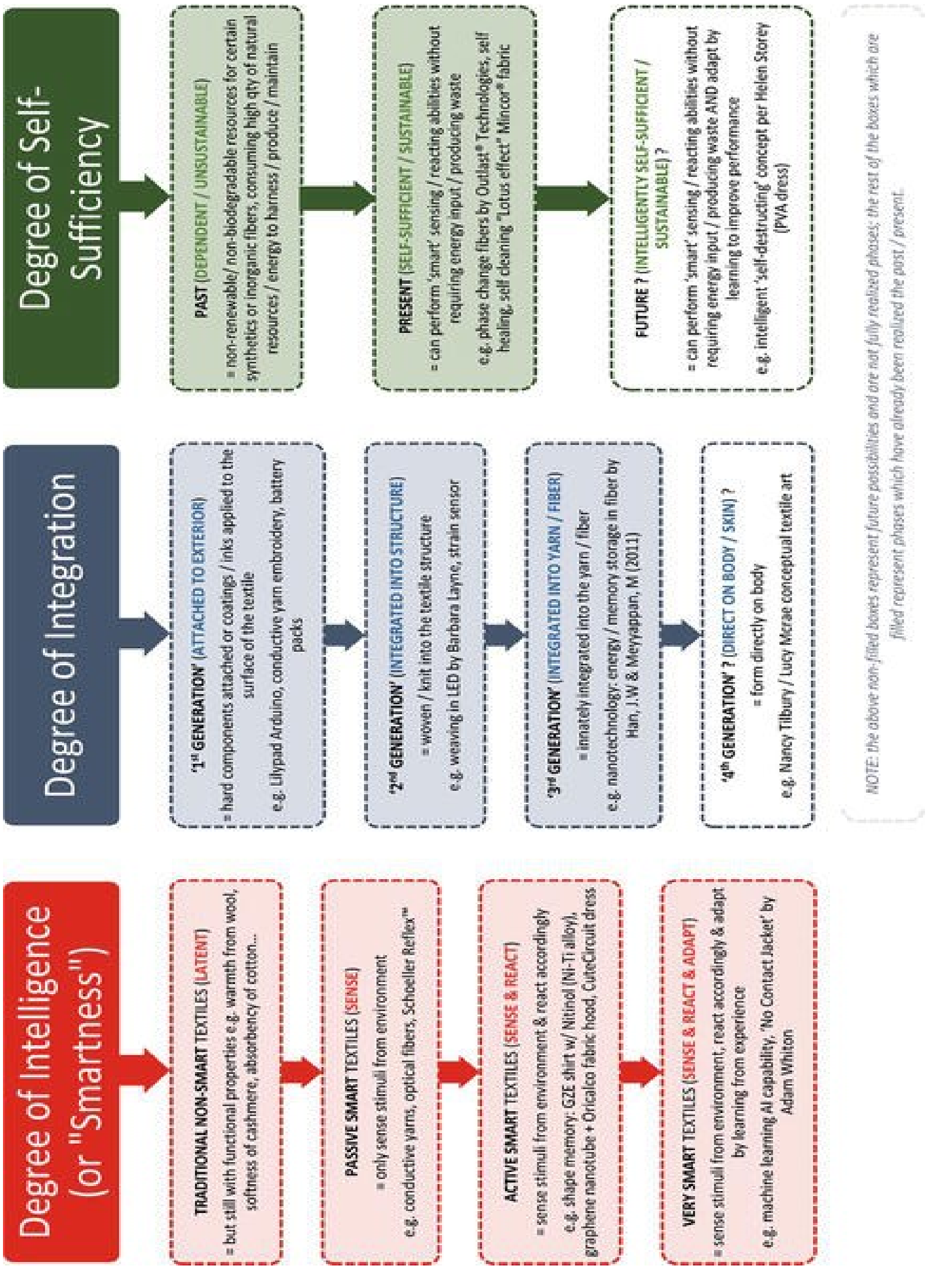


Figure 1. Flowchart that shows the evolution of e-textiles (Wu & Li, 2019, p. 7)

While traditional non-smart textiles can provide a certain functionality, they do not sense, react~~,~~ or adapt to external triggers (Wu & Li, 2019, pp. 6-7). The bare minimum for a textile to be smart, is when external stimuli can be sensed by the textile (passive smart textiles). When the textile is also able to react to the external stimuli, the textile can be classified as active smart. If a textile can adapt itself based on the external stimuli, the textile can be classified as very smart or ultra-smart textiles. This is the aim for the smart clothing market at the moment. (Çelikel, 2020, p. 1.)

As for degrees of integration, smart textiles have evolved from adding hard, bulky components to textiles (first generation), to knitting sensors into the finished textiles afterwards (second generation) and finally to adding the sensors already into the yarns. Embedding sensors during the production means that the smart clothing product becomes so comfortable that the difference with traditional textiles is hardly noticeable (third generation). Creating clothing using third generation smart textiles is the aim today. The fourth generation refers to textiles that would be able to anticipate external reactions and are part of the human body. These are only visionary concepts at this moment. (Wu & Li, 2019, pp. 7-8.)

Finally, smart textiles need power supply to perform. In the past, smart textiles were produced from non-renewable or non-biodegradable raw materials and both battery lifetime and laundry cycle for the textiles was very low. This resulted in a short lifetime and a lot of non-degradable waste. Presently, the increasing concern for carbon neutrality and sustainable materials has forced the smart textile community to evolve towards a degree of self-sufficiency evolution. Meaning that the smart textiles would be able to function self-sufficiently (i.e., being able to generate own power supply) and self-sustaining (i.e., energy-harvesting via body heat). The sustainability of the products is not an afterthought anymore, but inherently part of the production process. (Wu & Li, 2019, pp. 8-9.)

2.2 Industry 4.0

Since the 1800s, the world has gone through three industrial revolutions, each characterized by a new disruptive technology. First there was the steam engine, then the assembly line and thirdly the computer. These phases are called revolutions because apart from improving productivity and efficiency in production, it completely revolutionized how work was done and how goods were produced. (SAP, 2020.)

Currently, there is the Fourth Industrial Revolution, or Industry 4.0, which has taken the computerization of the Third Industrial Revolution to a whole new level. Industry 4.0 is built on nine technological pillars (Figure 2) that help make a connection between the physical and digital worlds – and as such, empower autonomous and smart systems. The nine technological pillars consist of (SAP, 2020):

1. Big Data and Artificial Intelligence (AI) Analytics: the computerization of the industry means that data is collected from many sources, varying from factory equipment, office programs, weather, and traffic apps. Analyzing the big amount of data (big data) using artificial intelligence allows for better decision making.
2. Horizontal and vertical integration: full integration amongst the industry processes, both on horizontal level (production processes across different facilities) and vertical level (from production facility to business processes like quality, sales, and marketing).
3. Cloud computing: the data generated from the Industry 4.0 technologies are stored on cloud servers which allows for faster access, more scalable infrastructure, bigger storage capacities and cost efficiencies.
4. Augmented reality (AR): AR allows to lay digital content over a real environment. Using smart glasses, an employee can for example see assembly instructions or training content for parts.
5. Industrial Internet of Things (IIOT): the physical things in Industry 4.0, think of machinery, robots, and devices, that use sensors and RFID tags to inform about their location, performance, or condition.
6. Additive manufacturing/3D printing: 3D printing means that the design of parts and products are stored as a digital file and printing is done on demand when the pieces are needed. This reduces both transportation and storage costs.
7. Autonomous robots: these robots allow to perform tasks with a minimum of human intervention.
8. Simulation/digital twins: a digital twin is a simulation of a real-world machine, product or system that uses IoT sensor data to generate the simulation. The digital twin gives insight to predict potential issues or identify malfunctioning parts.
9. Cybersecurity: the amount of gathered data within Industry 4.0 make cybersecurity crucial to minimize data breaches or threats.

A lot of these technologies are already used separately, but the full potential of Industry 4.0 will happen when all these technologies are combined more and more and are used together. (SAP, 2020.) The next chapter will focus on IIOT in more detail, as it is one of the most important components for Industry 4.0 and smart clothing can be seen as a IIOT application.

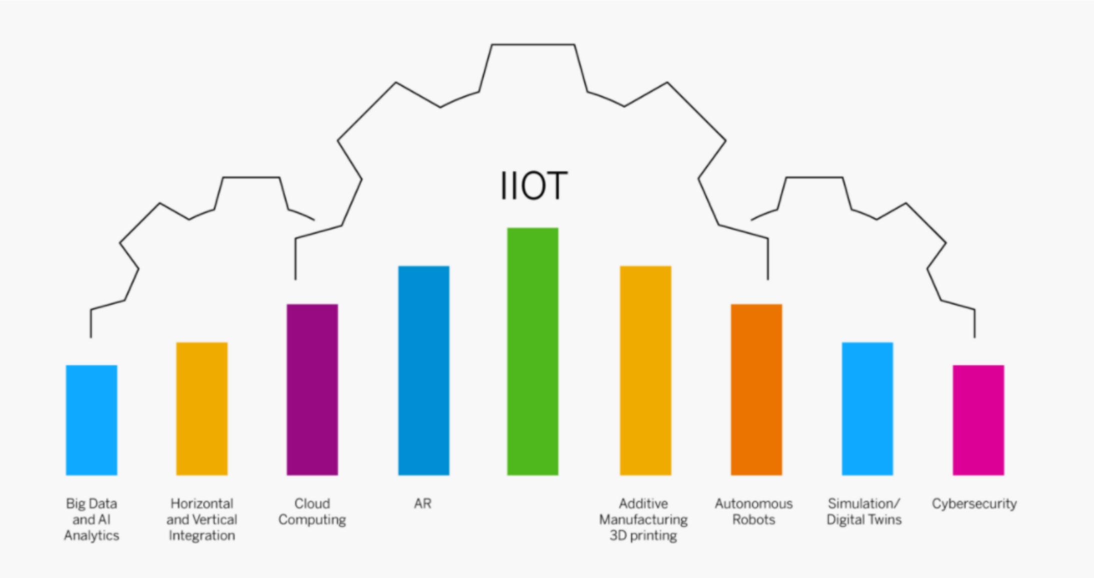


Figure 2. The nine technological pillars of Industry 4.0 (SAP, 2020)

2.3 Industrial Internet of Things (IIOT)

As shown in Figure 2 in the previous chapter, Industrial Internet of Things (IIOT) is one of the most important components for Industry 4.0. IIOT refers to using smart sensors and actuators that help improve manufacturing and industrial processes. The intelligent devices are connected into systems that help monitor, collect, exchange, and analyze data coming from “dumb” machines. The philosophy that drives IIOT is that smart machines are better at capturing and analyzing data than humans, but even more, the machines are better at communicating and transferring the data that can consequently drive business decisions more accurately and speedily. (Posey et al., 2021.)

Smart clothing can be seen as a next step in this IIOT – when everybody will wear clothing that is connected to a network, data can be used for improving the performance, productivity, and security of the employees. Examples of Internet of Things sensors that can improve employee's protection are (Ledda et al., 2019, p. 7):

- Immediate localization of workers in case of an emergency.
- Smart communication systems in helmets that allow for easier communication in dark or loud environments.
- Smart automation on machines (smart lock) to keep workers safe when they come too close to machines.
- Smart clothing that activates when high temperature (fire) or toxic gases are detected.
- Sensors that detect when personal protective equipment (PPE) are out of date or being misused by the workers.

2.4 Smart personal protective equipment

PPE, or personal protective equipment, is equipment which protects the wearer from occupational safety and health (OSH) risks. Smart PPE means that PPE is more smart, intelligent, and therefor might provide a higher level of comfort and protection. Often, the ´smartness´ is provided by electronics. Smart PPE is part of the IIOT. While the Industrial Internet of Things can also include machinery or specific grids of the workplace, smart PPE relates specifically to the worker. Heidi Lehmann, Chief Commercial Officer at Kenzen, states that the human factor is probably the most important component at any work site, so keeping the worker safe is of utmost importance. (Tesconsult, 2020.)

Many technologies, that are part of Industry 4.0, can be added to PPE to make them smarter. Examples are devices that can track personal localization (GPS), report geographical information system (GIS) or sensors that track body functions and environmental factors (such as humidity and temperature sensors). (Ledda et al., 2019.)

3 PURPOSE OF THE LITERATURE REVIEW AND RESEARCH QUESTIONS

While a lot of research on smart clothing dates back from before 2000, there are very few smart clothing applications on the market today. As mentioned by Heo et al. (2018) , most are still in prototype state and cost-effective ways to produce e-textiles or smart clothing on a large scale remains challenging.

This literature review aims to identify the current state of smart clothing for professional wear and analyze the factors that prevent production on large scale.

The main research question is:
Which factors are preventing manufacturers from producing smart clothing applications on a large scale?

To understand the challenges, it is important to understand the smart clothing applications as a whole entity. For this, the following sub questions will be answered:

- What are the different components of a smart clothing?
- What are the different manufacturing techniques for smart clothing?
- Which smart clothing for professional wear has been developed and taken into use since 2015?

4 RESEARCH METHODOLOGY

A scoping review was chosen as the research method for this literature review. This type of review is an exploratory analysis of potential size and scope of available research literature on a topic (Munn et al., 2018, p. 2).

4.1 Scoping review as the research method

A scoping review is particularly applicable to identify available evidence in a field, identify key characteristics related to a concept and clarify key concepts in the literature (Munn et al., 2018, p. 2). As such, this research methodology was appropriate for this literature review. Scoping reviews are also relevant to industries with emerging evidence, such as smart clothing industry, in which there are not enough trials done for researchers to perform a systematic review (Munn et al., 2018, p. 2). Especially in the field of smart clothing applications this is true, as the number of applications is developing so fast, there are limited studies available on how the applications perform in real life. Even though scoping reviews have a broader scope than systematic reviews, a scoping review still requires using transparent and meticulous methods to ensure the results are accurate (Munn et al., 2018, p. 6).

4.2 Search strategy and retrieval of studies

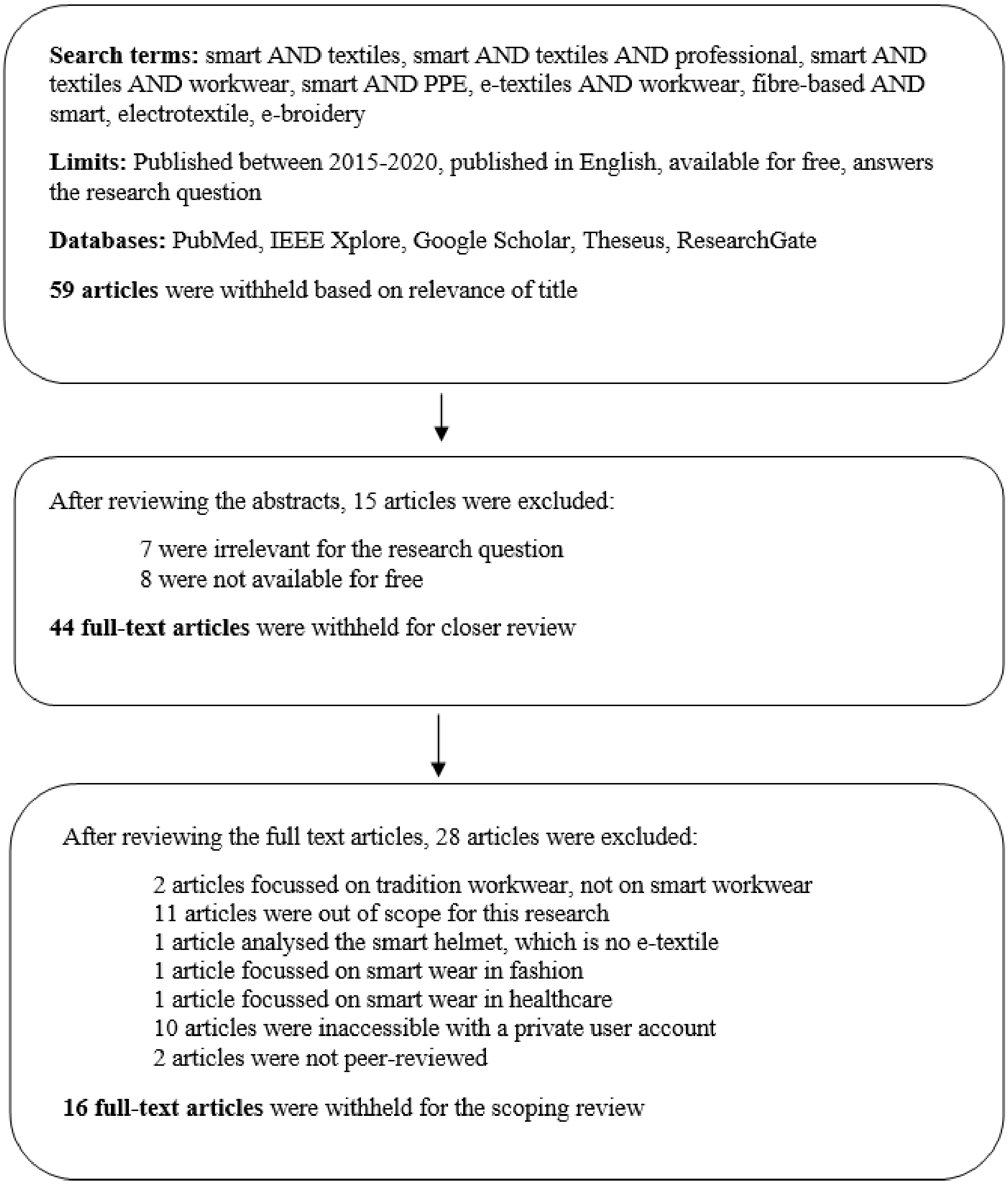
The research was started by defining the search terms and selecting the databases. After an initial exploratory search, PubMed, IEEE Xplore, Google Scholar, Theseus and ResearchGate were identified as the main databases.

To make the research focused and relevant, only studies performed during 2015-2020 were considered. The main reason is that technology has been changing so fast, that throughout the initial exploratory study for this research, it was noticed that applications or companies introducing smart clothing applications before 2015 as promising, were already out of business today. The defined inclusion and exclusion criteria can be found in Table 1.

Table 1. The defined inclusion and exclusion criteria

Inclusion criteria	**Exclusion criteria**
Published between 2015 and 2020	Published before 2015 or after 2020
E-textiles	Smart textiles not using electronics or technology
Published in English	Non-English literature
Accessible for free	Not accessible for free
Qualitative source (peer reviewed)	Lack of qualitative source (not peer-reviewed)
Relevant to the research questions	Irrelevant to the research questions.

Figure 3 shows the flowchart of the search process and keywords used. The keywords were the same for every database. The search was performed from November 2020 until January 2021 and closed on 31 January 2021. An overview of the withheld studies can be found in Appendix 1, table 2.



Search terms: smart AND textiles, smart AND textiles AND professional, smart AND textiles AND workwear, smart AND PPE, e-textiles AND workwear, fibre-based AND smart, electrotextile, e-broidery

Limits: Published between 2015-2020, published in English, available for free, answers the research question

Databases: PubMed, IEEE Xplore, Google Scholar, Theseus, ResearchGate

59 articles were withheld based on relevance of title

After reviewing the abstracts, 15 articles were excluded:

7 were irrelevant for the research question
8 were not available for free

44 full-text articles were withheld for closer review

After reviewing the full text articles, 28 articles were excluded:

2 articles focussed on tradition workwear, not on smart workwear
11 articles were out of scope for this research
1 article analysed the smart helmet, which is no e-textile
1 article focussed on smart wear in fashion
1 article focussed on smart wear in healthcare
10 articles were inaccessible with a private user account
2 articles were not peer-reviewed

16 full-text articles were withheld for the scoping review

Figure 3. Flowchart visualizing the search process

4.3 Quality appraisal of the selected studies

For assessing the methodological quality of the studies, the Johanna Briggs (JBI) Critical Appraisal Checklist for Qualitative Research was used (Appendix 2). This tool consists of ten evaluation criteria to assess the methodological quality of the included studies (JBI, n.d.). All 16 studies have been assessed, keeping in mind the limitations of the author of this work in assessing the studies. The author of this work has no academic or researcher background and the field is new. However, all included studies have been previously peer reviewed and been published in reputable scientific journals, so they already have gone through meticulous quality evaluation before publication.

4.4 Search strategy for current smart clothing applications

Throughout the reviewing of the 16 included studies, the author made note of the smart clothing applications for professional wear that were mentioned and researched in the studies. However, quite often the mention was rather short and did not always go into detail on the applications. The author of this work performed a different search in further investigating whether these smart clothing applications are still on the market and if so, what are the characteristics and technologies used.

The search was done via general search on Google, and the databases Google Scholar, PubMed, IEEE Xplore and ResearchGate. As most applications are still in prototyping phase, few studies on the status of the smart clothing applications were found. Only smart clothing applications for workwear that were mentioned in peer-reviewed journals or scientific research and that are still being productized today have been included in the results of this market research. This means that four extra articles have been included outside of the 16 articles from the scoping review. (Appendix 1, Table 3) These four studies have not been critically assessed.

Throughout the included studies, 53 companies and products were mentioned in the field of smart clothing. After research, only ten products were withheld for further analysis. These will be mentioned in chapter 5.4.

5 RESULTS

Fernández-Caramés & Fraga-Lamas (2018, p. 2) describe the ‘Internet of Smart Clothing’ as a world where smart clothes can communicate with each other, their environment and even Internet servers that enrich the wearables with advanced services. It will allow the smart clothing application to become enhanced based on the more data it receives. It also means that the e-textiles as such have no value, if there is no interface to read the data from, software to analyze the data and other technologies that allow data exchange with devices and systems over the internet. (Oracle, n.d.)

5.1 The different components of smart clothing

Fernández-Caramés & Fraga-Lamas (2018, p. 6) have visualized the architecture of a smart clothing (Figure 4). In this chapter we will look at the different components, or subsystems, in more detail to understand what a smart clothing application consists of. Only in understanding the different parts, the challenges and opportunities for smart clothing can be better understood.

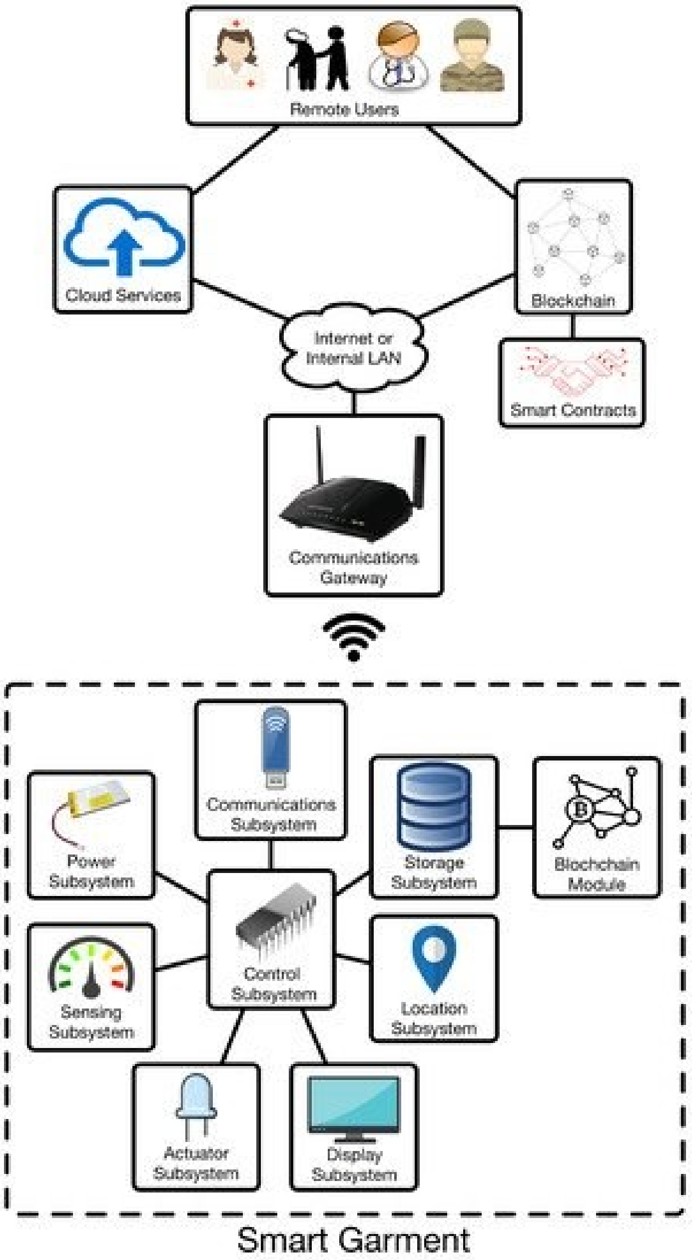


Figure 4. Generic architecture of an IoT smart garment system (Fernández-Caramés & Fraga-Lamas, 2018, p. 6)

5.1.1 Communication architecture

The communication architecture transfers the data coming from the smart clothing to the end-users. The architectural interface supporting the data collection and transfer, is illustrated at the upper part of Figure 4.

It consists of following components (Fernández-Caramés & Fraga-Lamas, 2018, p. 7):

- Communications gateway: a portal through which the information coming from the smart clothing device is sent forward to remote services, e.g., the cloud server or a blockchain. Not only is the communications gateway able to process data fast and push it forward, but the gateway also pushes the responses coming from the remote services quickly back to the smart garments.
- Cloud services: data can be stored and collected, for example on cloud servers, for access from remote users (e.g., doctors, nurses, employers) but also for the smart garments to access later.
- Blockchain: an optional component that can be added to smart garments for enhancing it with features like extra data security, trustworthiness and automation of certain tasks based on triggers, using Smart Contracts. IBM defines Smart Contracts as "programs stored on a blockchain that run when predetermined conditions are met". Smart contracts work by following simple "if/when…then…" commands. (IBM, 2021)

The architecture can be split up in three network layers, based on the range covered (Fernández-Caramés & Fraga-Lamas, 2018, p. 7):

- Body Area Network (BAN), or Wearable BAN (WBAN): the network of wireless sensors placed in very close proximity to the body that are collecting the biomedical data.
- Personal Area Network (PAN): this network collects the data from the smart garments and sends it to the cloud or remote server wirelessly (Wireless PAN; WPAN). An example of WPAN is Bluetooth. While PANs are recognized for their rather short ranges, a Local Area Network (LAN) is used for larger ranges (up to 10 meter). An example of a LAN is Wi-Fi (Wireless Internet for Frequent Interface).
- Wide Area Network (WAN): This network has a really big range, supported by a distributed infrastructure. The Internet is an example of a WAN.

5.1.2 Sensing subsystem

Sensor technology (Figure 4) has gone through a rapid change these last years. Multi-dimensional sensors are more a must than a differentiation factor today. Sensors have become smaller, cheaper to produce and more reliable. Previously, sensors might have been strapped around different parts of the body for measurement. The technological advancements have resulted in affordable, miniature, and accurate sensors available for clothing. Nanotechnology is the next step in sensor production. Coating or embedding the sensors in clothing allows an even further customizability and reduction in size. Also, threads like cotton, polyester, etc. have been adapted to be able to sense. Even completely new materials have been produced. (Hanuska et al., n.d., p. 31.)

The available sensors for smart clothing can be categorized according to the way they "sense" (Hanuska et al., n.d., p. 31):

- Physiological sensors can measure physiological reaction such as body temperature, sleep/rest quality, muscle engagement, perspiration rate and composition of urine, saliva or sweat, the amount of oxygen in the blood. These sensors help detecting injuries, trauma, or stress.
- Kinetic sensors measure steps, acceleration, cadence, location (Global Position System, also known as GPS), pressure, to name a few. Kinetic sensors can be used to detect stress and injuries as well, but also to generate electricity or even give tactical advantage for military troops.
- Agent, or environment, detection sensors can measure e.g., radiation, fungi, temperature, humidity, and chemicals. Their main function is detecting and avert dangers.

Furthermore, sensors can also interact with their environment by adding technologies (Fernández-Caramés & Fraga-Lamas, 2018, p. 8):

- Technologies such as infrared cameras can recognize objects around the wearer. RFID (Radio Frequency Identification) or Near Field Communication (NFC) tags that are attached to objects can be read from an NFC/RFID reader which is embedded into a smart clothing application.
- Sensors activated by tactile, e.g., mechanical switches, switch-tactile sensors, touch screens or fabric keyboards.

5.1.3 Actuation Subsystem

Actuators (Figure 4) allow to perform activities based on the information tracked by the sensors. An overview of the most common actuators in smart clothing using e-textiles are (Fernández-Caramés & Fraga-Lamas, 2018, p. 8):

- Visual indicators: light and information are shown through LEDs (Light-Emitting Diodes), optical fiber or displays.
- Sound: sound is emitted through buzzers, headphones, loudspeakers, or even ultrasound actuators (not hearable by the human ear).
- Movement and vibration: electricity is transformed into movement. Think of electric motors, vibration, solenoid (electromagnets).
- Heating and cooling: actuators able to use electricity for cooling or heating the smart garment wearer.

5.1.4 Control Subsystem

The control subsystem (Figure 4) are the brains of the smart clothing. It is the programmable part to steer the sensors what to track and how to process the information. Examples of control subsystems are Central Processing Units (CPUs), microcontrollers or Field-Programmable Gate Arrays (FGPAs). As the battery power in smart clothing is limited, the most common control subsystem in smart clothing are microcontrollers that are sewn onto the garments and programmed for the specific task of that smart garment. Microcontrollers are computational powerful and consume much less energy than any other processor. Lilypad Arduino or Adafruit are examples of DIY-kits (Do It Yourself-kits) that are freely available on the internet for sewing into the smart clothing garment and programming the specific tasks. (Fernández-Caramés & Fraga-Lamas, 2018, pp. 8-9.)

5.1.5 Communications subsystem

This subsystem makes it possible for the smart garment to connect to the Internet or to an internal LAN and opens a range of possibilities for enhancing the smart garment. The communication subsystem is responsible for two main tasks:

- Enable data transfer between the smart garment and communications gateway.
- Identify the wearer.

These tasks can happen through one or two dedicated physical transceivers. The most common identification technology is RFID that uses radio frequency tags for emitting unique identifiers. RFID-technology does not need a direct line of sight between the tag and reader, which is a huge advantage over other identification techniques such as barcodes or quick response (QR) codes. Moreover, passive RFID tags do not need batteries, which makes them very suitable for the smart garments. The range of passive RFID tags can be up to a few meters, but also battery-powered RFID tags (=active RFID) can allow a reading rang of up to hundreds of meters, however the size makes them then less suitable for clothing (Tanim, 2016, p. 5). In case longer reading ranges are necessary, certain technologies can be used that allow identification and data communication at the same time. Examples are Bluetooth Low Energy (BLE) or Wi-Fi, both of which allow reading signals between 50 and 100 meters. (Fernández-Caramés & Fraga-Lamas, 2018, p. 9.)

More and more new technologies are being used for the communication subsystem, for example ultrasounds, infrared, 3G/4G/5G, ANT+. Based on their frequency band, maximum reading range, data rate, power consumption and other relevant features, they can become more widely used in smart garments in the future (Fernández-Caramés & Fraga-Lamas, 2018, p. 9).

5.1.6 Location Subsystem

The location subsystem (Figure 4) allows to be able to position and track the exact location of the wearer of the smart garment. This technology is already well advanced and used by many wearables and other technologies (sport watches, smart phones).

The difficulty for smart clothing lays in tracking the wearer indoors. Received Signal Strength Indicator (RSSI) or Received Signal Strength (RSS) are typical parameters which are used in indoor positioning systems to estimate the location of an object. These parameters are very accurate when the situation is clearly defined, and the hardware placed correctly. As wearers of smart garments cannot be asked to stand in a specific location or do specific task to track them, alternative parameters need to be considered. Positioning parameters such as Angle of Arrival (AoA), Time of Arrival (ToA) and Time Difference of Arrival (TDoA) can be used to localize the wearer. AoA is the angle from which the signal, coming from the smart clothing sensor, arrives at a receiver whereas ToA refers to the time at which the wave arrives at the receiver. AoA and ToA are hard to get indoors because of lossy environment in which obstacles (walls, tables, other persons, etc.), may disturb and attenuate the radio wave propagation and thus signal may not be readable. That is why multiple receivers are needed to get the measurements right. (Srivastava, S., 2019.)
Other technologies that can enable positioning of a smart garment indoors are for example traditional cameras, ultrasound, infrared cameras, inertial navigation systems or Ultra-Wide Band (UWB). (Fernández-Caramés & Fraga-Lamas, 2018, p. 12.)

5.1.7 Power Subsystem

E-textiles cannot function without power. Batteries are still one of the most common energy storage devices, but also other technologies have emerged. One of these new technologies are supercapacitors, which have gone through major improvements these last years, and can already reach comparable energy quantity levels as lead-acid batteries. Other benefits of supercapacitors are environmental friendliness, fast charging and discharging speed and a long lifecycle. (Fernández-Caramés & Fraga-Lamas, 2018, p. 12.)

Depending on the type of device, different amount of power needs can be distinguished (Fernández-Caramés & Fraga-Lamas, 2018, p. 12):

- Low-end devices: have very low energy consumption and can be powered for a long time (years) with a small button-type battery. Traditional watches or pacemakers belong in this category. Components that use passive RFID tag don’t have any power source themselves but get powered through the reader signal (Tanim, 2016, p. 5).

- Mid-range devices: they use wireless communication receivers and can be powered up to a day when there are only periodic transmissions or a sleep mode. When they are transmitting continuously, the power supply only lasts several hours. This kind of devices require bulkier batteries (think of AA or AAA batteries) and are therefore less suitable for smart clothing.
- High-end devices: need Li-on batteries as the consumption is very high. Laptops and phones belong in this category. The bulkiness and added weight make them hardly appropriate for smart garments.

A lot of research and efforts have been made to reduce bulky, rigid batteries and make them more flexible for integration in smart clothing. There have been experiments with printing “flexible batteries” and provided protocols for designing ink. But when the clothing needs to be provided with high-power, no substitute for the current battery technologies has been found yet. (Fernández-Caramés & Fraga-Lamas, 2018, p. 13.)

Another possibility is applying technologies that use the energy coming from the body as energy-harvesting power: body motion and heat. Heat dissipating from the body could generate thermal energy that can be collected via, for instance, piezoelectric devices. Thermoelectric devices could harvest the mechanical energy coming from body motion.

Apart from the energy coming from the body, also power from the environment has been harvested already successfully:

- Sun can be harvested via photovoltaic cells.
- Wind can be collected via windmills.
- Electromagnetic waves surrounding us can be collected via specific energy harvesting devices.

Collecting the energy is not the only challenge, but smart clothes also need to be able to recharge. DC (direct current)-power jacks or USB (Universal Serial Bus) connections could be integrated into clothing, or wireless technology for recharging could be used. (Fernández-Caramés & Fraga-Lamas, 2018, p. 13.)

5.1.8 Storage subsystem

For Internet of Things applications, information is first processed lightly in the control subsystem after which it gets stored locally in EEPROM (electrically erasable programmable read-only memory) or SD (secure digital) cards. EEPROM can “store relatively small amounts of data by allowing individual bytes to be erased and reprogrammed” (Wikipedia, 2021). As IoT applications can store only limited amount of data, the further processing and analysis is done after the data has been uploaded to an external server. The information gets then processed further so the user can eventually access the processed data via a user interface. Think of a smart watch showing your workout on the phone application. An internet connection or Internal LAN enables the user to interact with the data gathered by the smart garment.

To improve security of the storage systems, blockchain has become more important in the storing and transfer of data in a secure way. (Fernández-Caramés & Fraga-Lamas, 2018, pp. 13-14.) Blockchain can be defined as “a peer-to-peer decentralized distributed ledger technology that makes the records of any digital asset transparent and unchangeable and works without involving any third-party intermediary. It is an emerging and revolutionary technology that is attracting a lot of public attention due to its capability to reduce risks and frauds in a scalable manner.” (Srivastava, N., n.d.)

5.1.9 Display subsystem

Smart clothing does not provide any integrated displays yet. As mentioned earlier, information is retrieved and consulted via an external (mobile) device. In the future, it might be good if external devices can be avoided by showing the information directly on the smart clothing. However, a display needs power and powering up smart clothing is difficult (see chapter 3.7.). LCD (Liquid Crystal Display) technologies have become more affordable but require too much battery life because of the need for backlight and continuous screen refreshing to display new information. New technologies such as OLED (Organic Light-Emitting Diode) and its variations need 20-80% less power than LCD screens, have a fast response time, high brightness, and contrast, but are more expensive than LCD.

The most suitable displays for smart clothing at this moment would be electronic ink displays, which are still more expensive than LCD for the consumer and are still only able to show grayscale images. There is also no backlight, so this would cause problems in low-light or dark scenarios. Other possible technologies, that still need further research, would be electrochromic and paper-like displays or technologies based on optical fiber. (Fernández-Caramés & Fraga-Lamas, 2018, p. 14.)

5.2 Different manufacturing techniques of smart clothing

E-textiles applications, or smart clothing for that matter, have been developed successfully, but the mass fabrication of e-textiles still proves challenging. Different than common wearables as smart watches, one of the critical characteristics for smart clothing is flexibility. Wearability will be compromised if the e-textiles are rigid and uncomfortable. For this reason, especially fiber-based integration of the electronics is being considered most favorable due to their flexibility, lightweight and comfort to wear. (Ismar et al., 2020, p. 1.)

Conventional textiles are lightweight, comfortable, washable, durable – e-textiles need to be developed in such a way that the same features are present, on top of including all the subsystems that allow the e-textiles to sense, act and communicate and be powered up to do all this. Electronic components are generally rigid, fragile, and hard. Any contact between a hard and flexible object is sensitive to stress and potentially breaking. For this, it is important to understand the different techniques that can be used to integrate the electronics to the textiles and making them e-textiles. (Stewart, 2019, p. 3) The five most common fabrication techniques to include electronics to textiles are: knitting, weaving, embroidery/appliqué, printing/coating , encapsulation (Stewart, 2019, pp. 4-5).

5.2.1 Knitting

Knitting (Figure 5) means that the yarn is looped in such a way that it becomes a fabric. The structure of this technique allows stretching after which it returns to original shape.

Knitting is an ideal technique for integrating stretch sensors and to produce garments that need to be worn close to the body (e.g., Lycra that has been electroplated with silver) (Stewart, 2019, p. 4).

5.2.2 Weaving

While knitting can be done from one yarn, different yarns or threads are needed to do weaving (Figure 5). When separate threads are woven together parallelly, it is called a warp. When weaving is not done parallelly but alternating the thread-weaving above and below the warp, it is called a weft. Weaving is useful when conductive threads need to be electrically isolated from each other. E.g., there can be electrical threads for the microcontroller, but separately also electrical threads for other circuits woven into the garment. (Stewart, 2019, p. 4.)

5.2.3 Embroidery or appliqué

Embroidery means that a thread is attached to the fabric afterwards. This technique allows for more flexibility on where to place the conductive elements, as it is not dependent on the structures of the woven or knitted fabrics. Anybody with a sewing machine can attach conductive threads, even without textile training.

Appliqué (Figure 5) is like embroidery; it is also attached to an already existing piece of fabric. But while embroidery attaches a thread to the fabric, appliqué attaches a new piece of fabric to the existing fabric. Appliqué is used to achieve higher conductivity, since conductive fabrics will have better electrical properties compared to individual conductive threads. (Stewart, 2019, pp. 4-5.)

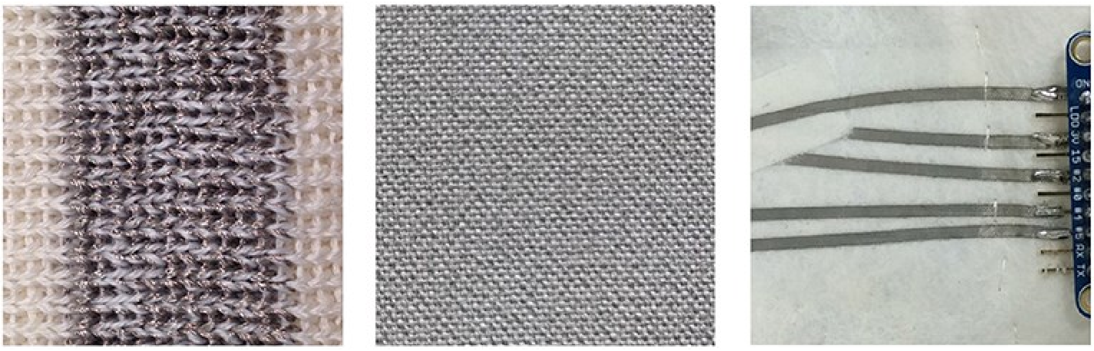


Figure 5. From left to right: knit conductive stripe, woven conductive fabric, appliquéd conductive fabric (Stewart, 2019, p. 5)

5.2.4 Printing and coating

Printing (Figure 6) can be done for example using a silkscreen or inkjet process, and it means putting ink onto the fabric using copper, silver, or carbon particle inks (= these generate conductive inks). Same as in embroidery, the conductive materials can be printed on places regardless of the textile structure (Stewart, 2019, p. 5)

Coating is an easy way to convert nonconductive textiles into conductive ones. Conductive solutions are put as a “coat” on the fabric, or the textile material is being immersed into the conductive solution. As electronic components are getting smaller in size, printing on fabric has gained more popularity recent years. When the printing can be laminated or sealed in isolated materials, it also improves the washability (Dabolina & Rainosalo, 2019, p. 87).

Laser printing will be the next generation in printing waterproof smart fabrics. Scientists from RMIT (Royal Melbourne Institute of Technology) University in Melbourne, Australia, developed a method to quickly laser print directly on textiles, enabling graphene supercapacitors – long-lasting and powerful energy storage devices than can easily be combined with solar or other power sources. This laser printing method will be a scalable and cost-efficient method; in just three minutes it is possible to produce a 10x10cm smart textile patch. Dr Litty Thekkakara, researcher in RMIT’s School of Science, said that “our graphene-based supercapacitor is not only fully washable, but it can also store the energy needed to power an intelligent garment and it can be made in minutes at large scale. By solving the energy storage-related challenges of e-textiles, we hope to power the next generation of wearable technology and intelligent clothing.” (Innovation Toronto, 2019.)

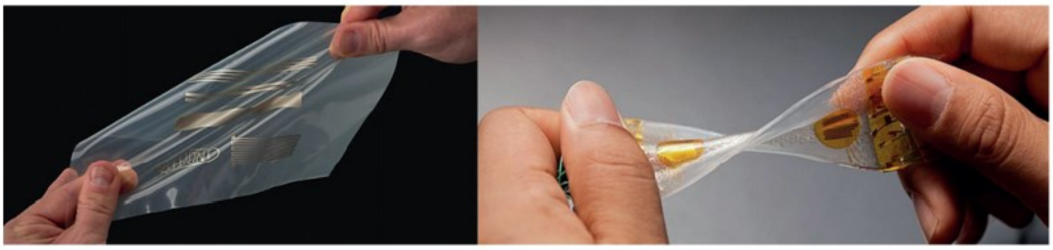


Figure 6. Electronic components printed on isolating or laminated materials makes them more resistant in washing (Dabolina & Rainosalo, 2019, p. 87)

5.2.5 Encapsulation

Encapsulation (Figure 7) means that extremely small electronics are embedded directly into yarns. Those yarns are then consequently woven into a textile. An example of this technique is adding OLED directly on a fibre to obtain a fibre-based wearable display (Kwon et al., 2018a, abstract).

Figure 7. Encapsulating fiber-OLED on a shirt (Kwon et al., 2018b, abstract)

5.3 The challenges in producing smart clothing

As this literature shows, a smart clothing application consists of a lot of different components that each impose challenges of its own. The current smart clothing applications for professional wear available on the market are still limited, and a lot are still in prototype phase. This chapter will discuss the main challenges the manufacturers face in producing smart clothing on large scale.

5.3.1 Challenges in collecting and analyzing data from smart textiles

The combination of structured, semi-structured and unstructured data collected by the sensors and e-textiles, can be described as big data. Big data can be defined by 3 V's: there is a large *Volume* of data in many environments, a *Variety* of data types stored in big data systems and data is generated, collected, and processed at a great *Velocity*. Challenges to work with big data include, but are not limited to (Botelho & Bigelow, 2019):

- Having the data processed in the cloud is a complex process. The processing capacity needs to be expanded to be able handle the data fast and reliably.
- Designing a big data architecture requires expertise, time, and budget.
- New software skills are required to deploy and manage big data systems.
- Accessibility to the data can be challenging in distributed environment that work with different platforms and data stores.

Although the term big data is already widely known, except in telecommunication and retail industry, these challenges are still cause for a slow adaptation of big data.
In smart clothing, interpreting the data coming from the sensors poses challenges. The data is often heterogenous as the sensors use different kind of technologies that produce non-uniform data. The data might be produced at uneven intervals, with temporal gaps, and have excess 'noise' (includes also irrelevant data). This makes analysis complex and poses difficulties in result confidence rates. Hanuska et al. (n.d.) state that smart clothing will not be able to conquer the market and be accepted within the market if these issues remain. (Hanuska et al., n.d., p. 35.)

Moreover, the exchange of data between different systems will have to be solved by avoiding propriety data formats. Data will have to be harmonized by using an open and standardized data format that gives the necessary information about the data acquisition and analysis. Secondly, a challenge will arise for comparing data between sensors that are calibrated differently. Manufacturers might use different filters, thresholds, or sample rates. (Hanuska et al., n.d., pp. 33-34.)

5.3.2 Challenges in privacy and security

Apart from the lack of a standardized data language, as discussed in the previous paragraph, there is also a consistent, and even growing issue of data security. The amount of collected data is alarming and especially wearable devices are a huge risk for security breaches. Data storage on the cloud, transmitted via e.g., Bluetooth, Wi-Fi, or RFID, have vulnerabilities for getting attacked by the wrong parties (Ching & Singh, 2016, pp. 8-9). Also, privacy issues remain a major challenge as data stored on the cloud can be available for many different parties. Wearables, and smart clothing as such, have no interface to enter a PIN (Personal Identification Number) or password, which makes implementing extra user security measurements tricky. Wearables are also activated all the time, and data is tracked continuously. While this offers extra possibilities for gathering data and reacting upon it, it also means more threats for the users' privacy being breached. (Ching & Singh, 2016, pp. 9-10.)

Finally, there is also the thread for workplace security. Bringing sensors, along with other wearables, on the work floor means that employers will have to increase intranet security, IT policies and employment regulation (Hanuska et al., n.d., p. 35).

5.3.3 Challenges in adaptability and liability

There are also cultural objections in using smart clothing on the work floor. The situation becomes very sensitive when data from wearables, like smart clothing, gets shared with third parties like the employer. It can be experienced as an intrusion to their privacy. Situational factors that provide extra security for the employee might raise the level of acceptance, e.g., detecting when an individual is exposed to a dangerous virus or gas. Laws and regulations will have to be put in place to regulate misuse and how data can be legally used by third parties. (Hanuska et al., n.d., p. 37.)

Heidi Lehman, cofounder of Kenzen, mentions that the supervisor at a work site is quite often important in the effectiveness of using the gathered data. If the worker gets an alert because his or her stress levels are too high, or body temperature is at a dangerous level, it is often hard for the worker to acknowledge that a break is needed. Firstly, they do not want to seem weak towards their supervisor and other work mates and secondly, the workers feel the pressure to get the job done (Tesconsult, 2020).
A workshop organized by the German Commission for Occupational Health and Safety and Standardisation (KAN) amongst firefighters showed that the continuous storage and collection of the wearer´s data is an important concern. The users want to know which data is traced and enable and disable the tracing themselves. (Thierbach, 2020, p. 6.)

Privacy and security issues also emerge on the employer’s side. If a certain risk is spotted by the wearable (e.g., bad posture by a nurse or soldier in danger), and the employer fails to react – will it mean the employer will be liable? These are very sensitive issues which need to be regulated to guarantee a widespread acceptance level of the smart clothing in a professional environment. (Hanuska et al., n.d., pp. 37-38.)

5.3.4 Challenges related to lack of standards and legislation

Dr. Michael Thierbach (2020) at The Occupational Safety and Health Administration (OSHA) addresses the fact that PPE must be tested according to PPE regulations to get the correct certification. Both users and employers take comfort in the fact that e.g., safety shoes or helmets are conforming the necessary safety regulations when they purchase them for the workplace. (Thierbach, 2020, p. 3.)

The same will have to apply for the smart clothing or PPE; the testing will have to be done in its entity. It will not be sufficient to test the PPE and then the electronic parts separately. Testing the smart PPE in its entity will ensure electrical safety, surface temperature, impacts of electromagnetic fields (EMF), electromagnetic compatibility (EMC) and battery safety. (Thierbach, 2020, p. 3.)

Also, for the testing procedures, it is important that the manufacturers get guidelines on how the smart PPE needs to be tested and which testing methods to use. As the testing needs to be done already during the design phase, the lack of a testing standards is an obstacle for many manufacturers to even start considering investing time and money in developing smart PPE. (Thierbach, 2020, p. 7.)

5.3.5 Washability

Dabby et al. (2017) have researched the washability of wearable electronic sensors, that is tracking ECG (electrocardiogram) and heart rate measurements. The testing showed that all samples' results were still properly functioning after washing for ten times, but damaged after 25 washing cycles. Their research mentioned that especially severe stretching and twisting that happens during the washing spoiled the sensors. Chow et al. (2018) used conductive threads to embed textile pressure sensors in socks. Their research showed that the performance of the sensors was decreased significantly after 15 washing.

Apart from the huge impact that the washing machines have on the e-textiles, the conductivity and durability are also affected by exposure to light, the washing detergents, and possible chemical treatments. Up to this date, there is still not enough research on the long-time reliability of e-textiles after the endured wear and tear that clothes undergo during their lifecycle. If there is no guarantee that the e-textiles can withstand washing, commercial success will remain an issue. (Ismar et al., 2020, p. 9.)

5.3.6 Other challenges

Apart from the previous mentioned challenges, there are still a wide variety of other challenges that influence the success of smart clothing. Dolez et al. (2020, pp. 4-5) defined a list of foreseeable problems that can be associated when using smart textiles for Occupational Health & Safety applications:

- Potential harm for health and safety: issues have been raised in the potential toxicity of metals and nanoparticles, accidental electric shocks, the effects of continuous exposure to electromagnetic fields and the lack of an emergency switch-off button. Also, ethical issues have been raised in regards of personal safety data and information management in the workplace.

- Incompatibility issues and interference with other technologies: the effect of smart clothing in combination with other electronics (e.g., pacemakers) and communication systems has not been sufficiently researched yet. Same goes for possible electric shocks that might occur when sweating obtrusively or being in heavy rain while wearing smart clothing.
- Accessibility issues. Smart clothing is not accessible freely on the market yet. This poses limitations for using it in OH&S (Occupational Health & Safety) environment; the cost might be too high, or accessories might be needed for the smart clothing application to be functioning properly. An example is the availability of RFID-readers at the working gates which would be able to read the RFID-tags integrated in the safety harnesses.
- Real value for the user is not yet validated. There is still not enough proof available that the benefits of using smart clothing applications are outweighing the possible negative side effects and additional costs.
- End-of-life challenges. As there are still issues with the durability of smart clothing, disposing of smart textiles poses similar challenges as getting rid of e-waste. Sensors and batteries can often not be detached from the application, which makes it hazardous and problematic waste. It will be critical to ensure that smart textiles waste does not create new risks for health and environment when disposing of them.

5.4 Smart clothing applications in production and productization

This chapter will focus on the smart clothing applications currently available on the market for professional wear. It is important to mention is that only applications mentioned in the research studies published between 2015 and 2020, and using e-textiles, have been considered in this chapter. When the research studies have mentioned certain applications, they have been researched further to determine whether the applications are still being productized or on the market. Only smart clothing applications that have appeared in other media (industry-specific magazines or journals) than just on their own website have been considered for this review.

5.4.1 Smart PPE for workers in waste management

As stated by Ledda et al. (2019), the waste management industry is one of the most hazardous employment environments in Europe. The National Institute for Insurance against Accidents at Work (INAIL) has studied how Industry 4.0 applications can increase safety in workplaces. Technologies such as smart factory or Internet of Things (IoT) allows for workers to be found in case of emergency thanks to GPS system, control the access to dangerous areas thanks to sensors and even to give instructions directly to the workers thanks to Augmented Reality (AR). (Ledda et al., 2019, p. 1.)

INAIL has researched the use of smart PPE in waste management, and its compliance to European and Italian laws and regulations. Employees active in waste management are required to use PPE that includes Respiratory Protective Equipment (RPE), safety helmet, high-visibility clothing that protects against heat, rain and/or cold, gloves, non-slippery footwear, ear and eye protection. Depending on the type of exposure or job the workers are performing in waste management, the PPE changes. The research aims to show if additional smart functions increase current PPE performance, optimize the workers' productivity, and decrease costs. (Ledda et al., 2019, p. 1.)

At the time of research, most smart PPE used in Solid Waste Management (SWM) are using Bluetooth beacon technology or RFID-tags applied to PPE. This allows to trigger an alarm for example in case of the PPE´s non-detection (off the grid). Other smart PPE applications use RFID sensors or tags that restrict access to dangerous areas, and to make sure the workers have the right kind of PPE for that area and are using it correctly. Also face recognition or area control software might be used to identify workers accessing certain areas. Finally, Physical Security Information Management (PSIM) is used to anticipate accidents or "near misses" and to identify possible dangerous situations. (Ledda et al., 2019, pp. 9-10.)

As adopting smart PPE is expensive and requires extensive experience and knowledge of IoT and IT systems, not all companies have the resources to start using them. Therefore, INAIL developed in 2019 a new piece of smart PPE, using cheaper components (Figure 8). A 'normal' PPE was transformed to a smart PPE, using sensors via both physical and wireless connections that are connected to a small control unit. Thanks to the combination of other devices, data coming from environmental sensors can be connected to the data of the employee's health data. Added accessories can allow the smart PPE to trigger a "reaction" to the data as well: visual or acoustic warnings can be produced for the worker, information can be sent to the emergency control room, parts of the PPE can be heated or cooled, or tactile feedback can be provided. INAIL stated in 2019 that the prototype aims to merge different sensors and technologies so that a full suite of solutions can help protect the workers from many risks. At the end of the project, the aim is to provide both the software and hardware for free for the companies in solid waste management. (Ledda et al., 2019, p. 10.) Unfortunately, this project was started in 2019 and no studies could be retrieved on the results or the current situation of this smart PPE.

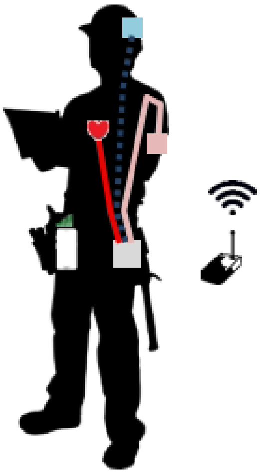


Figure 8. The schematic overview of the smart PPE that INAIL developed (Ledda et al., 2019, p. 10)

5.4.2 Smart clothing applications for manufacturing industry

The smart clothing applications described in this chapter can be used in a variety of manufacturing and/or construction industries. They are not limited to one type of work activity, but rather can be used in different kind of environments.

5.4.2.1 Smart Vest to detect metal

Rajendran et al. (2020) developed a safety vest that includes metal detectors and consequently can warn the worker immediately when a metal hazard is around. For the creation of this product, commercially available parts were used and combined into a single working entity. The smart safety vest developed for this project, will be particularly useful for warning construction workers when metal impact is about to happen. (Rajendran et al., 2020, p. 537.)

Figure 9 shows the different components that were used in creating the safety vest. The DIY (Do-It-Yourself) metal detector kit consists of electronic components assembled on a printed circuit board (PCB) of 6x6 cm. As the whole kit is light-weighted, it should not cause any uncomfortableness to the wearer. The kit is connected to a copper coil and sewn into the safety vest at the front and back. It is powered by batteries that can be recharged using solar energy. This allows for a low maintenance cost. Also, an on/off-switch is included, so the vest can also be worn when no warnings need to be triggered and metal detection is allowed (when workers are specifically working with metal). The prototype produces a beeping sound and light whenever a metallic object approaches the copper coil. These warnings are particularly useful for workers at low visibility locations. (Rajendran et al., 2020, pp. 537-538.)

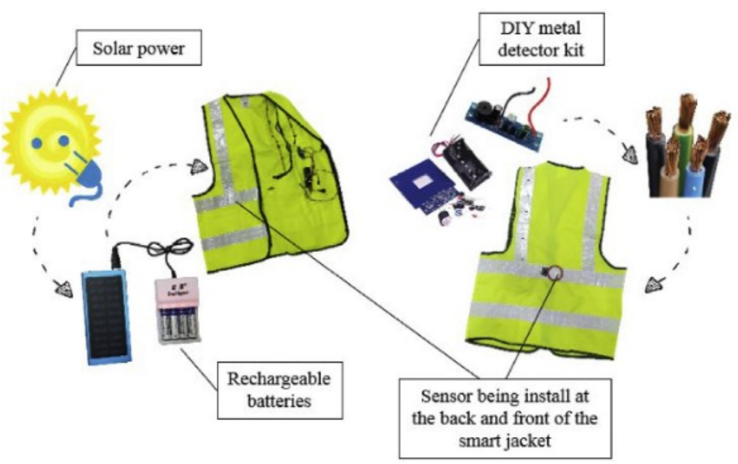


Figure 9. Overview of the different components used for the prototype of the smart safety vest (Rajendran et al., 2020, p. 538)

This safety vest was tested among 121 respondents that rated the vest above average for simplicity in design, usability, lightweight and environmental friendliness. The main challenge was that the detection distance is very low (4 cm), so it needed further development to improve its usability. Also upgrading the vest to allocate a tracking system connected to the internet would be beneficial so the employer can track where the metal hazard occurs. (Rajendran et al., 2020, pp. 539-540.)

The metal vest was a prototype and at the time of writing this scoping review no information was available on how feasible the large-scale production of the safety vest is. The researchers conclude that production will be possible at an affordable price when investments in proper manufacturing techniques and business plan are done (Rajendran et al., 2020, p. 541).

5.4.2.2 Vest that lower risks for getting work-related musculoskeletal disorders (MSD)

Yang et al. (2018) developed a vest that integrated textile electrodes and motion sensors to transfer real-time data wirelessly (via Bluetooth) to a mobile application (Android tablet). Data such as leg motion and heart rate were analyzed to track the impact of different types of activities and levels of workload done by the wearer of the vest.

The aim of the vest (Figure 10) was to investigate how combining new technologies and textile production can be used to detect risks related to physical workload, assess the feasibility and usability of the prototype and to obtain insights for further smart work clothing development. (Yang et al., 2018, p. 1.)

Figure 10. The smart vest includes four textile electrodes, that are used for measuring electrocardiogram (ECG) and thoracic electrical bio-impedance (TEB) (Yang et al., 2018, p. 3)

The vest was used in four different scenarios: postal delivery, construction work, office work, and car driving. Without going in detail about the specifics of the study, risk levels of each job were analyzed using the average relative aerobic strain (RAS). The RAS was calculated using the ratio between the oxygen consumption and the VO_{2max} (maximal aerobic capacity) of the worker. If the RAS percentage exceeded 33%, the work tasks were categorized as high risk (imposing a too high energy demand on the worker). Percentages lower than 25% were classified as safe. Any percentage between 25 and 33 meant that the work task could impose a risk and needed further analysis. (Yang et al., 2018, pp. 40062-40064.)

The study of the vest showed the potential of using a wearable system in assessing the risks during work activities. The vest was considered easy to wear and did not bother the test persons. However, limitations on using the vest for a long term were mentioned, such as powering the vest for longer time (when wearing the vest for a full 8h workday) and the robustness of the textile electrodes might be compromised when wearing longer (too much movement, sweat). Also, the measured physiological data were not used to assess stress, further analyzing the measurements could be an opportunity to enhance this vest. (Yang et al., 2018, pp. 40067-40069.)

A similar product to this vest is BioHarness, developed by Zephyr Technology, already in 2011. Up to this date, it is freely available on the market, but it is just a strap measuring a range of health data such as ECG, respiration, blood oxygen saturation, posture, and acceleration. As the technology is already tested and matured enough, other systems have also started to use it for integration with their own products. It is being used to e.g., measure the stress levels of firemen, soldiers, and astronauts. (Scataglini et al., 2015, p. 1.) As it is just a strap, not a clothing as such, it will not be further discussed in this scoping review.

5.4.2.3 Smart Workwear System

In physically demanding jobs, it is important to improve the working conditions to reduce or mitigate the risk in getting work-related musculoskeletal disorders (WMSDs). Sweden’s innovation agency VINNOVA funded a project in analysing how making smart textiles part of the workwear can influence this risk. The project was carried out by Hultafors Group, a leading manufacturer of regular workwear. Scania CV, Volvo Trucks and Volvo Cars participated as partners in the project. (Lind et al., 2018, chapter 2.)

During the project, a prototype of Smart Workwear System (Figure 11) was developed and tested. The system integrates sensors and electronics in the workwear, to measure heart rate, breathing, forces exerted, postures and movements. Signals are recorded and analysed in real-time. The system is in contact with either a virtual coach or human coach, that will inform the wearer of the system about the recorded results immediately, giving feedback on wrong postures or work techniques. (Lind et al., 2018, chapter 3.)

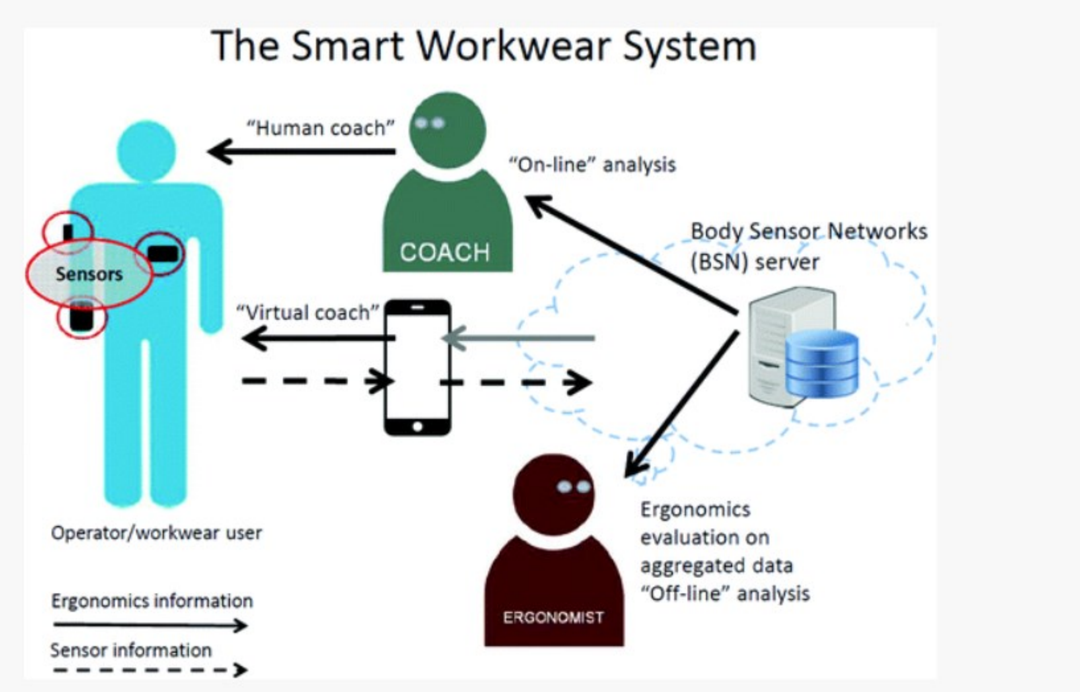


Figure 11. Architecture of the Smart Workwear System (Lind et al., 2019, chapter 3)

The Smart Workwear System was tested amongst three groups, during which the differences were analysed when the test persons got feedback from either the human coach, the virtual coach or feedback from a ´normal´ coach that got no data from the system. Although more extensive testing and research will be needed, the test persons that got feedback from the virtual coach experienced less exposure to bad posture and risk handling compared to the other two test groups. More studies will have to show if this was thanks to the system or rather just because of individual learning effects. Apart from the real-time analysis, the data is stored on a server for aggregating data to allow ergonomics analysis both on group and individual level. (Lind et al., 2018, chapter 4-5.)

5.4.2.4 Smart clothing applications for construction sites

The VTT Technical Research Centre of Finland has designed a protype that can warn the workers of hazards on construction sites. The prototype is part of the ConIoT project, which is aiming to make construction sites safer by using smart clothing and data analytics. The ConIoT prototype consists of a smart work jacket, that is equipped with an LED optical fibre and an advanced IoT system. (Partanen, 2020.)

The system collects location data from the construction machinery and from the sensors of the jacket. Data analytics and a reporting system process the data to an appropriate format so it is readable for those who need it, and warnings can be triggered to the correct recipient when hazardous situations are close. The project also uses artificial intelligence (AI), as 1700 hours of data have been used to teach the system in recognizing the work activities of the workers. The AI technology is already able to detect different work tasks with almost 90% accuracy. Next step will now be to teach the AI to recognize exceptions to the normal work patterns. Recognizing when a worker is on heights and tracking deviations from the normal working patterns might possibly prevent falls when alerting the workers in time. (Partanen, 2020.)

Another aim will also be to detect hurried work, as hurry is both a safety and quality risk in construction. The AI system could notify the worker to relax their pace or notify the site management that extra hands are needed. (Partanen, 2020.) The prototype was announced to be ready by the end of 2020, after which it will be launched for the general public.

5.4.2.5 Smart masks

Myant Inc, which is a worldwide pioneer in textile computing, announced in September 2020 concept designs for smart mouth masks that would use VOC (volatile organic compounds) sensing. The masks are part of the Skiin collection, a collection of interconnected biometric garments for everyday life. Apart from workplace use, the masks will also be introduced in fitness and healthcare industry. The masks are modular, consisting of a filtration layer that separates airflow coming from nose and mouth, a flexible silicone seal and a knitted textile cover that includes heated and electrostatic yarns. (Figure 12) The conductive yarns are connected to a module that sends the data to the user’s mobile device via Bluetooth. (Hannah, 2020.)

Figure 12. The modular smart masks which are part of the Skiin collection (Hannah, 2020)

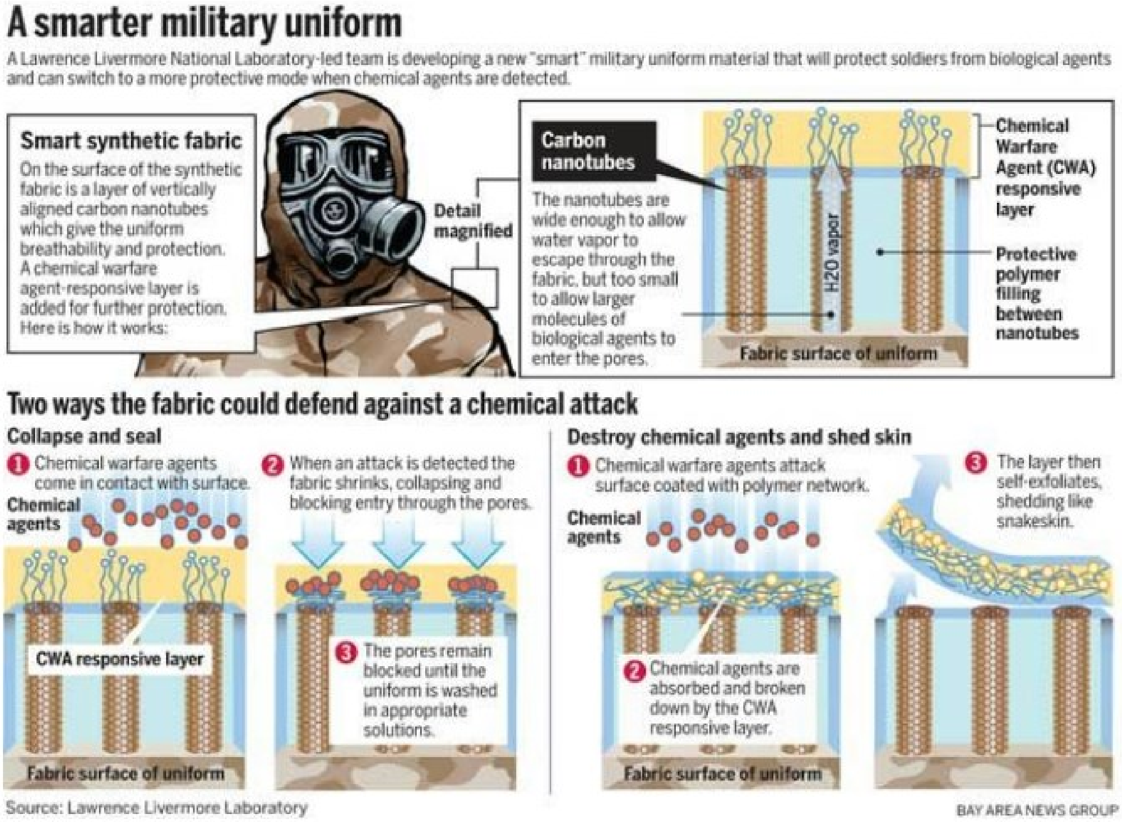
The yarns enhance protection against infections and enable the sensing of the respiration rate, VOC, sweat, saliva, carbon dioxide, body temperature and heart rate variation. This data is captured and sent to the Myant platform where AI technologies can generate insights that can help to improve health and performance: stress sensing, fatigue monitoring or even early outbreaks of diseases. (Hannah, 2020.)

A common concern of wearing masks is the trapped air which stays inside the mask and can cause fatigue. The smart mask separates the oral and nasal airflows via the nose-bridge, so air exhaled from the mouth will not go back into the body. The filtration system in combination with the VOC sensors can identify possible airborne infections. (Hannah, 2020.) The smart masks were announced to be launched during the last quarter of 2020, but no information about the launch could be found during the writing of this study in the spring of 2021.

5.4.3 Smart clothing applications for military

The Lawrence Livermore National Laboratory has been researching the development for a fabric for military uniforms that would be able to protect against both biological and chemical warfare (Figure 13). The fabric consists of miniscule holes, that are large enough for sweat to come out, but small enough that viruses or bacteria are prevented

to come in. The fabric can react to chemicals; upon detection the fabric can either close the holes or peel off to protect the wearer. (Hanuska et al., n.d., pp. 24-25.)
The fabric and its findings were announced in the press in 2016, calling it the soldiers' 'second skin' (Verger, 2016). At that time, it was anticipated that the fabric would be ready for use within 10 years' time. No other research was found after that time.



Source: Lawrence Livermore Laboratory

Figure 13. The smarter military uniform developed at the Lawrence Livermore National Laboratory (Hanuska et al., n.d., p. 25)

5.4.4 Smart clothing for astronauts

In 2017, NASA (National Aeronautics and Space Administration) tested the Astroskin Garment (Figure 14); a garment that can continuously track physiological events of the astronauts. The washable shirt has several embedded sensors that track the activity levels (3-axis accelerometer), heart rate (HR) & heart rate variability (HRV), respiration rate, oxygen saturation, blood pressure and skin temperature. In 2017, it was planned that warning alerts and decision support capabilities would be further developed for future garments. (Toscano et al., 2017, p. 7.)

Figure 14. The Astroskin garment. A shirt originally developed for astronauts (Toscano et al., 2017, p. 7)

The Astroskin was consequently used at the International Space Station (ISS) in 2018 and has gone through several developments since then. It is one of the smart clothing garments that is still on the market. Today, the Astroskin can be bought also by consumers as it is purchasable online (Hexoskin, n.d.).

Another smart garment that has been used on board of the ISS, is the Bio-Monitor (Figure 15). It is in many ways like Astroskin. The smart shirt is a wireless shirt that can sense and measure following biometric date: pulse and electrical heart activity, breathing rate and volume, blood oxygen saturation, skin temperature, blood pressure, and physical activity levels. The shirt can be worn continuously, also during sleeping and exercising. The tracked data is sent to the scientist on the ground, so the astronauts' health can be tracked around the clock. (Canadian Space Agency, 2021.)

Figure 15. Overview of what the Bio-Monitor shirt tracks and how it works (Canadian Space Agency, 2021).

In 2019, it was mentioned that the shirt can also be worn in hazardous working environments as mines, factories, and industrial sites (Canadian Space Agency, 2021). However, no additional literature was found that this smart shirt is actively used in these industries today.

5.4.5 Smart clothing for firefighters

Smart protective clothing for firefighters might be one of the most well-known smart clothing today. Different sensors are integrated in the protective firemen’s clothing and measure physiological functions such as blood pressure, body temperature and heart rate. This data allows to assess the work capability of the firefighter and trigger an alarm if e.g., heart rate or body temperature exceeds a certain rate. Apart from physiological measurement, environmental sensors are also added to detect toxic gasses or extreme heat. Finally, information about the condition of the protective garment is available to detect whether all protective characteristics are still intact after an assignment and the right level of protection can still be guaranteed for future tasks. All this data improves the level of protection for the firefighters and their ability to do the job without putting themselves at risk. (Thierbach, 2020, p. 1.)

The Smart Clothing 2.0 Project is a project, in association with VTT Technical Research Centre of Finland Ltd, and several other companies, that developed a wearable technology solution for the real-time monitoring of heat stress of firefighters. The current smart clothing application on the market that have heating elements, still need manual adjusting of the heating. The Smart Clothing 2.0 has developed an autonomous control system, that can adjust the heating based on the wearer's personal needs. The system analyzes the ambient temperature and the wearer's own heat generation, the activity level, and the individual body composition to adapt to the right heating. The aim of the project is to bring the technology to the consumer market to be available for various users. (Textile Today, 2019.)

6 DISCUSSION

The aim of this scoping review was to identify the current state of smart clothing for professional wear and analyse the factors that prevent production on large scale. The scoping review included 16 articles and discussed 10 smart clothing applications that are currently either in prototype or on the market. Only smart clothing applications using e-textiles - textiles and clothing that are fabricated using technology and electronics - have been considered for this scoping review.

6.1 Discussion of the results

Throughout the research, 53 company names or smart clothing products were mentioned but further research indicated that most of the products are not yet developed enough or were taken of the market again. This scoping review did not focus on the factors that caused these smart clothing to fail. Rather, this scoping review focussed on products launched after 2015, that are being productized or already on the market. By analysing the products, the review aims to find common factors on their manufacturing techniques.

The scoping review showed that eight of the ten products are still in prototype phase. Seven of those seem to use appliqué or embroidery as the main manufacturing technique. This means that the sensors are sewn in after the production of an existing piece of clothing. Sewing in sensors afterwards is time-consuming and makes it difficult to produce on a large scale. One product in prototype not using embroidery, but rather knitting or weaving with conductive yarn, is the smart mask of Myant Inc (Hannah, 2020).

Only two out of the ten analysed products are currently being produced on a large scale and available for purchase: Astroskin and Bio-Monitor. And although no research could be found on how these products are manufactured, the visualisations of the shirts show that the sensors are fully integrated. It is therefore safe to assume that the encapsulation technique has been used. Both Astroskin and Bio-Monitor are used for fitness purposes as well and can be bought by private persons. Smart products within the fitness and Business-to-Consumer industry are already more developed and have been widely accepted, so from the manufacturers' point of view it made sense to invest in more expensive production techniques (embedded sensors) (Hanuska et al., n.d., pp. 14-18). The same logic pertains to the smart masks as those are also envisioned to be useful for fitness purposes (Hannah, 2020).

The manufacturing technique seems therefore one of the success factors for smart clothing. Encapsulation or knitting and weaving with conductive yarns means that the sensors are embedded in the yarns already before starting to create the piece of clothing. This makes it a much more durable solution that can endure washing and it is also more comfortable to wear. Apart from the products Astroskin, Bio-Monitor and the smart mask, the other seven products are using rather bulky electronics, so they are still in the first generation of integration. (Wu & Li, 2019, p. 7)

Although it might be fine to experiment with DIY-kits during prototyping phase, smaller, more flexible electronics will be needed when production is done on large scale. Bulky, uncomfortable clothing might not be accepted by the users. It is also noticeable that all ten products in this scoping review are only passive smart, so the garments are only able to sense the stimuli without being able to react on it (Wu & Li, 2019, pp. 6-7).

Apart from the manufacturing technique, the number of different components of a smart clothing each pose a number of challenges on their own: sensors need to be developed and integrated into the clothing in a way that they withstand the wear and tear of washing and wearing, indoor location tracking is difficult, batteries need to be flexible and small – but still powerful, data needs to be stored to a microprocessor with enough memory to store the data when a phone is not close. Different than a smart watch, there is no solution yet for having a display integrated on the clothing. And apart from the different components that impose technical challenges, there are also several challenges in the adaptability of the smart clothing.

Especially when considering workwear, there is the concern that employees do not want the employers to track their health performance. Frameworks will need to be developed to allow the employee to enable or disable the tracking of data themselves. Only if the employees understand the value for them, that sharing the data can improve their safety and health, smart clothing at work might have a chance to be accepted. Also, ethical issues are important to mention. Tracking health data means that the devices may need to go through medical device certification, which poses extra costs and testing standards for the manufacturers. The employer will furthermore expect that necessary laws are put in place to protect them from liability in case an accident cannot be avoided, even if the smart clothing triggered warnings. More testing will have to be done to show the reliability of the smart clothing over a long period of time; after it has endured sweat, rain, and other strains of wearing.

Although the research field has been investing a lot of time in creating prototypes, there are still few manufacturers that start to invest in creating production lines for producing the products on a large scale. If there are no testing standards and certifications in place, the manufacturers might not want to take on the risk in producing smart clothing that would not be accepted by their user group (employers that only buy PPE which carries certain safety certifications). This is the biggest obstacle for manufacturers to take the products any step further than just prototype phase. Producing on large scale means many big initial investments, which are too risky if the challenges are not taken care of.

Strategic alliances will have to be formed between the manufacturers of clothing, insurance providers, unions for protecting the rights of workers and big data storage providers. Each have an expertise of their own, and these partnerships will be key in the success of this smart clothing industry. (Hanuska et al., n.d., p. 12.)

More than the technological challenges, the legislation on sharing health data will be a huge factor influencing success. Exactly for this reason, more smart clothing applications for fitness purposes are already on the market, as the health data is not shared with anybody without specific consent and no liability issues come into the picture. As mentioned earlier, no manufacturer will further invest in producing on large scale if these issues are not resolved.

This scoping review offers a lot of information and details about the different components of smart clothing and the detailed overview of the current smart clothing applications for professional wear could not be found from any other research so far. This scoping review has only considered the timeframe 2015-2020 and as this is a very fast changing field, the results of this scoping review might become outdated fast. Further research would be recommended to analyze if the eight applications in this scoping review that are still in prototyping phase will appear on the market, and if so, what has been their success rate. It would also be beneficial to research why so many applications from before 2015 have failed so fast. Finding out these reasons would allow to make a comparison with the products mentioned in this scoping review: have those used better manufacturing techniques or technologies? It is important to reiterate that only smart clothing using e-textiles have been considered for this scoping review. An additional scoping review focusing on smart materials that are not using electronics might be useful to compare the current situation in that field. So, this scoping review only scratched the surface and further research would be recommended.

6.2 Limitations of the scoping review

Before concluding the scoping review, the author of this work recognizes the limitations of this scoping review. As only freely accessible publications were considered, important research might not have been included. This would especially be true in research on the current market status of smart clothing, as those studies were not available free of charge. The topic of smart clothing was also new for the author, and although a lot of time was spent in researching the topic much more in detail than only the 16 included articles, it still means that the analysis of the technical challenges has remained on a broad level and have not been discussed in detail. The research was also done by only one person, although it is generally recommended to have at least two researchers review the articles. The lack of experience in doing a scoping review can also be considered a limitation for this review.

6.3 Trustworthiness & ethical issues

Only peer reviewed articles, collected from reliable databases, have been included in the scoping review. Inclusion and exclusion criteria were set from the start and used throughout the research. In case terms were not understood, extra peer-reviewed research was gathered so the author could familiarize herself with the materials.

The collection of the findings has been documented carefully and no subjective choices have been made for the selection of the articles. The authors of the publications are always mentioned, and the sources used are reliable and chosen with high standards.

As the scoping review has been conducted by one person only, that has limited experience in the field and in research, negligence errors can occur that may affect the results or the scoping review.

7 CONCLUSION

This literature review has analysed the challenges that prevent manufacturers to produce smart clothing for professional wear on a large scale. For this, the research sub-questions were also answered:

- What are the different components of smart clothing?
- What are the different manufacturing techniques for smart clothing?
- Which smart clothing for professional wear has been developed and taken into use since 2012?

The scoping review showed that a smart clothing component consists of nine different components which are continuously being further developed: the communicational architecture and the sensing, actuation, control, communications, location, power, and storage subsystems. Each component poses its own technological challenges which can explain why the development of smart clothing is still in its early stages. The most common production techniques are still embroidery and appliqué, meaning that sensors are put into the finalized clothing afterwards. Smart clothing manufactured using conductive yarns threads (by weaving, knitting printing or encapsulation) are still hard to find today.

Already early in 2000, research mentioned that smart clothing would be the next booming business after the wearables (Tao, 2001, pp. 3-4). However, today, 2021, the amount of smart clothing applications is still limited, and most applications are still in prototype phase. Earlier developed products, products that were described as ‘promising’ before 2015 have already disappeared from the market.

The described challenges showed that the lack of standards and regulations is particularly limiting companies to experiment and invest in the development of smart PPE. Also, a framework will have to be developed on how to tackle the privacy issues that come with sharing your health data with your employer. Technology is still not mature enough, even though the research has advanced considerably and working prototypes show that there is potential. But as long as the standards and regulations are missing, no production on large scale can or will happen.

There is no doubt that finally the smart clothing applications will be widely available on the market. The research and innovations are continuously developing, and the prototypes are promising. More research would be recommended to see why so many smart clothing applications have failed and if the prototypes in this scoping review will finally be launched on the market. Another scoping review, focussing on smart clothing using smart materials, instead of e-textiles, would also be recommended.

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Table 2. Overview included studies in the scoping review.

Author(s), Year	**Title**
Wu & Li, 2019	An Introduction to Wearable Technology and Smart Textiles and Apparel: Terminology, Statistics, Evolution, and Challenges
Dolez et al., 2020	Applications of smart textiles in occupational health and safety
Rajendran et al., 2020	Design of a Smart Safety Vest Incorporated With Metal Detector Kits for Enhanced Personal Protection
Zaman et al., 2020	Development of E-textile electrodes: washability and mechanical stresses
Ismar et al., 2020	Futuristic Clothes: Electronic Textiles and Wearable Technologies
Lind et al., 2018	Prevention of Work: Related Musculoskeletal Disorders Using Smart Workwear – The Smart Workwear Consortium
Dãbolina et al., 2019b	Smart Clothing – Report of laboratory tests of smart clothing technologies and materials
Dãbolina et al., 2019a	Smart Clothing - Survey of existing wearable technologies and needs of end-user segments
Hanuska et al., n.d.	Smart Clothing Market Analysis
Thierbach M., 2020	Smart personal protective equipment: Intelligent protection for the future
Fernandez-Caramés & Fraga-Lamas, 2018	Towards The Internet of Smart Clothing: A Review on IoT Wearables and Garments for Creating Intelligent Connected E-Textiles
Ledda et al., 2019	Using smart PPE in waste management: advantages and disadvantages
Çelikel, 2020	Smart E-Textile Materials
Stewart, 2020	Cords and Chords: Exploring the Role of E-Textiles in Computational Audio
Yang et al., 2018	Towards Smart Work Clothing for Automatic Risk Assessment of Physical Workload
Scataglini et al., 2015	A Review of Smart Clothing in Military

Table 3. Overview added studies for the smart clothing applications currently on the market.

Author(s), Year	**Title**
Partanen, 2020	Smart clothing protects builders
Hannah, 2020	Myant Unveils Connected PPE Concepts, Creating New Ways to Assess Health and Performance as Part of the Skiin Interconnected System of Biometric Garments.
Toscano et al., 2017	Wearable biosensor monitor to support autonomous crew health and readiness to perform
Textile Today, 2019	Smart clothing with improved comfort and safety for future firefighters

APPENDIX 2

JBI CRITICAL APPRAISAL CHECKLIST FOR QUALITATIVE RESEARCH

Reviewer____________________________________Date_____________________________

Author____________________________________Year________ Record Number________

	Yes	No	Unclear	Not applicable
1. Is there congruity between the stated philosophical perspective and the research methodology?	☐	☐	☐	☐
2. Is there congruity between the research methodology and the research question or objectives?	☐	☐	☐	☐
3. Is there congruity between the research methodology and the methods used to collect data?	☐	☐	☐	☐
4. Is there congruity between the research methodology and the representation and analysis of data?	☐	☐	☐	☐
5. Is there congruity between the research methodology and the interpretation of results?	☐	☐	☐	☐
6. Is there a statement locating the researcher culturally or theoretically?	☐	☐	☐	☐
7. Is the influence of the researcher on the research, and vice- versa, addressed?	☐	☐	☐	☐
8. Are participants, and their voices, adequately represented?	☐	☐	☐	☐
9. Is the research ethical according to current criteria or, for recent studies, and is there evidence of ethical approval by an appropriate body?	☐	☐	☐	☐
10. Do the conclusions drawn in the research report flow from the analysis, or interpretation, of the data?	☐	☐	☐	☐

Overall appraisal: Include ☐ Exclude ☐ Seek further info ☐

Comments (Including reason for exclusion)

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