

CHALLENGES IN PRODUCING SMART CLOTHING ARTICLES FOR PROFESSIONAL WEAR

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ABSTRACT

The purpose of this paper is to analyse the challenges preventing manufacturers from producing smart clothing for professional wear on a 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 the final prototype stage. 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 lie 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.

Keywords: Smart Clothing, e-textiles, smart work wear, smart PPE

INTRODUCTION

Wearable technology has experienced significant growth over the past two decades, driven largely by the proliferation of mobile devices and the rapid advancement of the Internet of Things (IoT) (Figure 1). Wearables like fitness trackers and smartwatches enable users to monitor various physiological functions, providing insights into physical activity, sleep patterns, and stress levels. Parallel to this evolution, there have been multiple efforts to embed electronics into garments, thereby transforming conventional clothing into smart wearables (Ju & Lee, 2020). While accessories such as smartwatches and earbuds have reached widespread commercial adoption, the smart clothing segment remains underrepresented in the consumer market despite substantial academic and industrial research (Wu & Li, 2019).

This study aims to explore existing smart clothing applications in the context of professional wear and to identify barriers impeding their large-scale production. A critical distinction must be made between conventional and smart textiles. While traditional textiles offer physical functionalities, such as warmth, breathability, and protection against environmental elements, smart textiles are capable of sensing external stimuli and responding accordingly (Ismar *et al.*, 2020).

Although the terms “smart textiles” and “e-textiles” are often used interchangeably, they differ in scope.

According to the “Standard Terminology for Smart Textiles” issued by the American Society for Testing and Materials (ASTM) in 2019, smart textiles do not necessarily contain electronic components, whereas e-textiles are characterized by embedded electronics (ASTM International, 2019). This research focuses primarily on e-textiles, which are defined as garments integrated with electronic functionality. The term “smart textiles” in this context will be used synonymously with “e-textiles,” unless otherwise specified.

The integration of sensors during the production process enhances comfort and wearability, rendering third-generation smart clothing virtually indistinguishable from conventional apparel. This generation aims to achieve seamless functionality, while fourth-generation concepts envision fully integrated, bio-interactive textiles that can anticipate environmental stimuli and operate in synergy with the human body. However, the latter remains speculative and conceptual at present (Wu & Li, 2019).

A critical component of smart textiles is the power supply. Historically, many smart textiles were developed using non-renewable or non-biodegradable materials, resulting in short product lifespans and considerable waste due to limited battery life and wash durability. In light of increasing environmental awareness and the global push for carbon neutrality, there is a growing imperative for

self-sufficient and sustainable e-textiles, garments that can generate power through mechanisms such as energy harvesting from body heat. Today,

sustainability is no longer an afterthought but a fundamental aspect of smart textile development (Wu & Li, 2019).

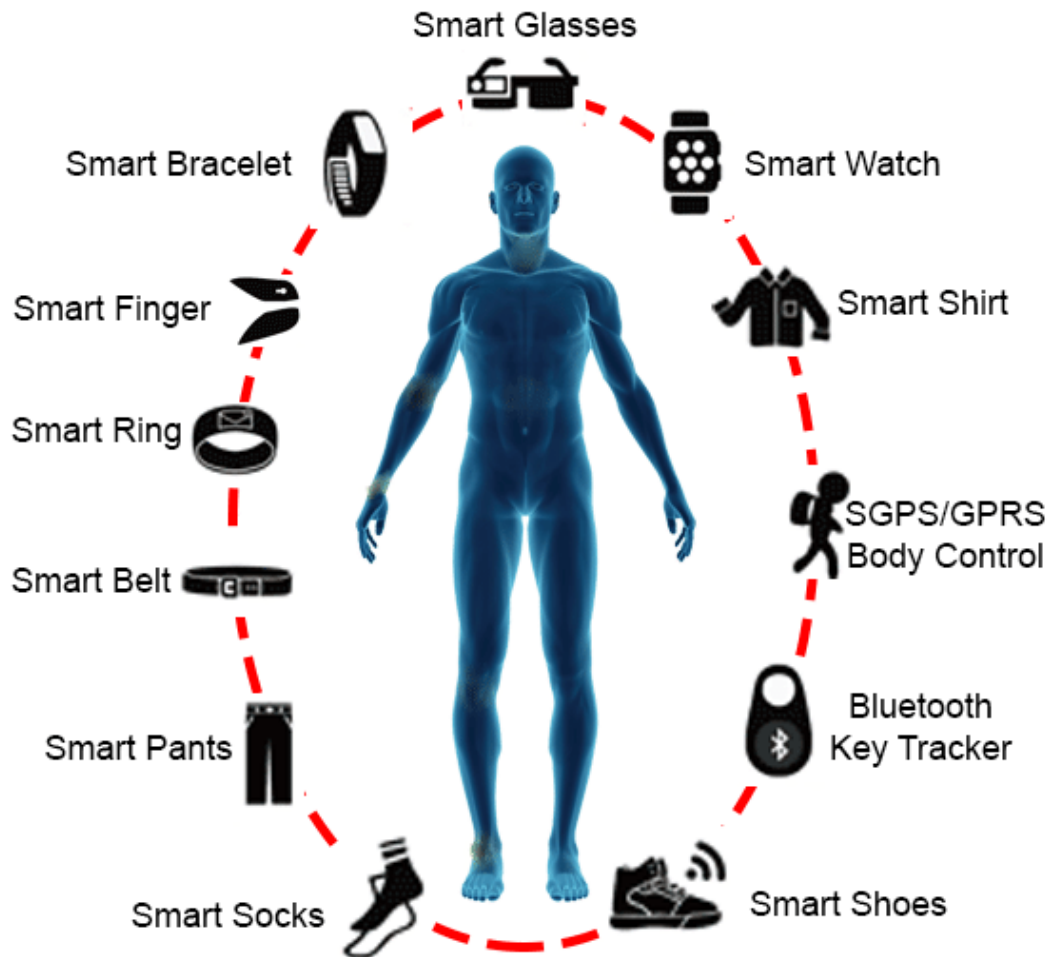


Fig. 1: Different types of wearable technology (Rodrigues et al., 20218)

The emergence of Industry 4.0 has introduced nine key technological pillars that provide the foundation for the future of smart textile manufacturing (SAP, 2020):

1. Big Data and Artificial Intelligence (AI) Analytics: Leveraging vast datasets generated from diverse sources such as factory equipment, logistics systems, and environmental sensors to improve decision-making processes.
2. Horizontal and Vertical Integration: Seamless integration of operational processes both across production facilities and throughout the supply chain, encompassing design, quality control, sales, and marketing.
3. Cloud Computing: Enabling scalable data storage and real-time data accessibility, thereby optimizing operational efficiency.
4. Augmented Reality (AR): Enhancing user interaction through digital overlays, for example, by providing assembly instructions via smart glasses.
5. Industrial Internet of Things (IIoT): Interconnecting machinery and devices via sensors and RFID tags to enable continuous monitoring of performance and condition.
6. Additive Manufacturing (3D Printing): Facilitating on-demand production and digital design storage, thereby reducing transportation and warehousing costs.
7. Autonomous Robots: Performing tasks with minimal human intervention, thereby improving productivity and safety.
8. Simulation/Digital Twins: Creating digital replicas of physical systems for predictive maintenance and performance monitoring.
9. Cybersecurity: Safeguarding vast quantities of industrial data from breaches and cyber threats.

Although many of these technologies are already employed independently, their full transformative potential will only be realized when they are increasingly integrated and utilized synergistically (SAP, 2020).

Industrial Internet of Things (IIoT)

Among the aforementioned pillars, the Industrial Internet of Things (IIoT) is particularly critical for the textile industry. IIoT refers to the deployment of intelligent sensors and actuators in manufacturing systems to enhance performance, data exchange, and process automation. These systems enable “dumb” machines to become interconnected and self-monitoring, thereby facilitating data-driven decision-making. Smart machines outperform humans in data capture, analysis, and communication, making IIoT a key enabler of operational efficiency (Posey et al., 2021).

In professional settings, IIoT technologies enhance employee safety, productivity, and security. Examples of IIoT applications for occupational safety include:

- a) real-time worker localization in emergencies;
- b) smart helmet communication systems for noisy or dark environments;
- c) proximity-based machine lock systems for injury prevention;
- d) garments with heat and gas detection capabilities;
- e) PPE sensors that alert for misuse or expiration of equipment (Ledda et al., 2019).

Smart Personal Protective Equipment (PPE)

Personal protective equipment (PPE) refers to gear designed to protect workers from occupational hazards. When augmented with electronics, PPE becomes “smart,” offering enhanced protection and user comfort. Smart PPE is a subset of IIoT and focuses specifically on safeguarding the human element in the workplace. According to Heidi Lehmann of Kenzen, the human factor is the most vital component at any worksite, making worker safety paramount (Tesconsult, 2020).

Various Industry 4.0 technologies can be integrated into PPE to enhance functionality. These include GPS tracking devices, GIS systems, and biosensors capable of monitoring environmental and physiological conditions (Ledda et al., 2019).

Objectives of the Study: This study aims to explore the current landscape of smart clothing applications, particularly those designed for professional use. The

primary objectives are twofold. First, the study seeks to analyze the existing smart clothing technologies and how they are applied in professional settings. Second, it aims to identify the major challenges that hinder the mass production and widespread adoption of these innovations.

Research Questions: In line with the study’s objectives, two key research questions guide the investigation. The first question examines how smart clothing applications for professional wear are currently being designed and implemented. The second question explores the obstacles that prevent the large-scale production and integration of smart clothing into professional environments.

MATERIALS AND METHODS

Research Design

This study adopts a scoping review methodology, which is appropriate for mapping the existing body of literature, identifying core themes, and clarifying concepts in rapidly evolving fields (Munn et al., 2018). Unlike systematic reviews, scoping reviews are particularly well-suited for areas where empirical evidence is still emerging, such as smart clothing. Given the swift pace of innovation and the limited availability of performance data on real-world applications, a scoping review provides a rigorous yet flexible approach for synthesizing relevant insights. Although broader in scope, scoping reviews still adhere to transparent and methodologically sound procedures to ensure accuracy and reliability (Munn et al., 2018).

Challenges in Smart Clothing Adoption

Lack of Standards and Regulatory Frameworks:

Thierbach (2020) emphasizes the necessity of regulatory compliance in certifying PPE. Users and employers expect that workplace safety gear, such as helmets or safety footwear, complies with established standards (Thierbach, 2020). The same expectations must apply to smart PPE, which should undergo holistic testing as an integrated system rather than evaluating electronic and textile components separately. This comprehensive testing is necessary to ensure electrical safety, surface temperature control, electromagnetic compatibility (EMC), and battery reliability (Thierbach, 2020).

Manufacturers must also receive clear guidelines on appropriate testing methodologies during the product design phase. The absence of standardized procedures constitutes a major barrier to innovation and investment in smart PPE development (Thierbach, 2020).

Washability and Durability: The longevity and commercial viability of e-textiles are closely tied to their washability. Dabby *et al.*, (2017) evaluated the durability of wearable ECG and heart rate sensors, finding that most retained functionality after 10 wash cycles but degraded significantly after 25. Chow *et al.*, (2018) similarly reported that textile pressure sensors embedded in socks exhibited performance degradation after 15 washes. In both cases, sensor failure was attributed to mechanical stresses (stretching), twisting and environmental exposure during laundering.

Factors such as exposure to light, detergents, and chemical treatments further compromise conductivity and durability. Currently, insufficient data exists on the long-term reliability of e-textiles subjected to routine wear and care. This lack of durability assurance remains a significant impediment to commercialization (Ismar *et al.*, 2020).

Dolez *et al.*, (2020, pp. 4–5) provide a comprehensive overview of obstacles impeding the adoption of smart textiles in occupational contexts. These include:

Health and Safety Risks: Potential hazards associated with smart clothing include the use of toxic or allergenic nanoparticles, the risk of electric shock, extended exposure to electromagnetic fields, and insufficient emergency shut-off features for embedded electronics. These concerns demand thorough safety validation and regulatory oversight before large-scale deployment.

Cost and Economic Viability: The high cost of development, integration, and maintenance of smart textiles limits their affordability and scalability. Employers are unlikely to invest in high-cost smart PPE without demonstrable improvements in safety, productivity, or cost-saving outcomes.

User Comfort and Ergonomics: Smart textiles must not compromise user mobility, thermal comfort, or tactile sensation. Added weight from embedded electronics, loss of flexibility, or discomfort due to hard components can lead to user rejection.

Data Privacy and Security: Many smart PPE systems collect sensitive physiological and location data. The absence of standardized protocols for data encryption, anonymization, and storage raises serious ethical and legal issues, especially in jurisdictions with strict data protection regulations.

Workforce Acceptance and Cultural Barriers: Resistance to technological adoption in traditional industries, such as construction or mining, can hinder implementation. Training, awareness campaigns, and clear demonstration of benefits are critical to user acceptance.

Maintenance and Lifecycle Issues: The hybrid nature of smart textiles, combining electronics with soft materials, poses unique maintenance challenges. These garments may require special cleaning procedures, periodic calibration, or component replacement, raising operational costs and logistical complexity.

Discussion

Smart textiles and e-textiles hold transformative potential across various professional sectors, including construction, mining, manufacturing, healthcare, and emergency response. Their ability to monitor worker health, detect environmental hazards, and enable real-time communication promises to enhance occupational safety and productivity. However, the successful commercialization and widespread adoption of smart clothing are contingent upon resolving critical challenges related to standardization, durability, affordability, user acceptance, and regulatory compliance.

To bridge the gap between laboratory innovation and real-world application, a multi-stakeholder approach is essential. Regulatory bodies must establish clear guidelines and safety standards tailored to the unique attributes of smart textiles. Researchers should prioritize the development of washable, flexible, and biocompatible electronic materials that withstand repeated use and cleaning. Manufacturers need to adopt scalable and cost-effective production methods, possibly leveraging advances in printable electronics and conductive polymers.

Moreover, integrating ethical and legal considerations into the design process, especially those concerning data privacy and worker consent, will be crucial for gaining societal trust. Cross-sector collaboration among textile engineers, computer scientists, healthcare professionals, policymakers, and end-users will accelerate the translation of prototypes into commercially viable products.

Conclusion

Despite significant advancements in smart textile research, practical implementation in the realm of professional clothing remains limited due to unresolved technological, regulatory, and socio-

economic challenges. This scoping review has identified key barriers to commercialization, including the lack of standardized testing protocols, limited durability during washing and daily use, potential health risks, and ethical concerns related to data security. Future work should emphasize the development of robust testing frameworks, long-term durability studies, environmentally sustainable power solutions, and interdisciplinary collaborations. Only by addressing these multifaceted challenges can smart professional clothing achieve large-scale adoption and contribute meaningfully to the future of occupational safety and performance in the age of Industry 4.0.

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