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Status, opportunities, and future of smart personal protection equipment in construction site: Patent analysis

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Abstract

Personal protective equipment (PPE) plays a vital role in ensuring workers' safety on construction sites. This study aims to analyze the current state, opportunities, and future trends of PPE through a systematic patent analysis, providing insights into its technological advancements and development strategies. A comprehensive patent analysis was conducted by searching and evaluating relevant databases to categorize the main types of PPE used in construction, including helmets, protective eyewear, safety shoes, and safety belts. The study assessed the technological level and innovation of each type of equipment. Furthermore, emerging opportunities in PPE development, such as smart wearable devices, the application of IoT technology, and advancements in material science, were explored to align with market demand and technological trends. The results indicate that PPE in construction is evolving towards enhanced intelligence, connectivity, and performance efficiency. Innovations in smart wearables and IoT integration are improving real-time monitoring and adaptive safety measures. Additionally, material research is driving advancements in durability and user comfort. These developments collectively contribute to a more comprehensive safety framework for construction workers. With continuous technological progress and increasing safety awareness, PPE in construction is expected to achieve significant breakthroughs in intelligence and humanization. Future strategies should focus on improving comfort, adaptability, and comprehensive protection to enhance worker safety. This study provides theoretical support for PPE development and practical references for industry stakeholders, including manufacturers, policymakers, and construction firms. The findings offer guidance on optimizing PPE design and functionality to align with evolving safety needs in construction environments.

Keywords: Construction site, Patent analysis, Personal protective equipment, Safety management, Smart wearable devices.

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1. Introduction

Construction sites are high-risk environments where workers are exposed to hazards such as falls, collisions, puncture wounds, and exposure to hazardous substances. PPE is used in various construction activities to reduce these risks, including helmets, protective eyewear, safety shoes, harnesses, gloves, and respiratory protection [1]. In 2021, around 340 million recorded occupational accidents occurred globally, and 50% of those construction site workers wore PPE [2]. According to the latest data available on 31 May 2024 from the Web of Science (Fig. 1), from 1992 to 2024, many countries like the USA and China have been trying to develop new Smart PPE devices. Each type of equipment is designed to protect specific parts of a worker's body from injuries caused by occupational hazards. For example, head protection caps are one of the oldest and most frequently used PPEs to protect against direct impacts to the head from objects such as debris, falling equipment, and moving machinery [3]. In recent years, the design and functionality of PPE have been improving with the continuous advancement of technology and people's safety awareness. The application of new materials and technologies, such as smart wearable devices and IoT technologies, is gradually entering the PPE market, providing new opportunities and challenges to enhance workers' safety and security. For example, A study has constructed a high-quality dataset of 1,330 images based on the You Only Look Once (YOLO) architecture for helmets, people, and vests, including four colors for checking whether a worker is wearing PPE [4].

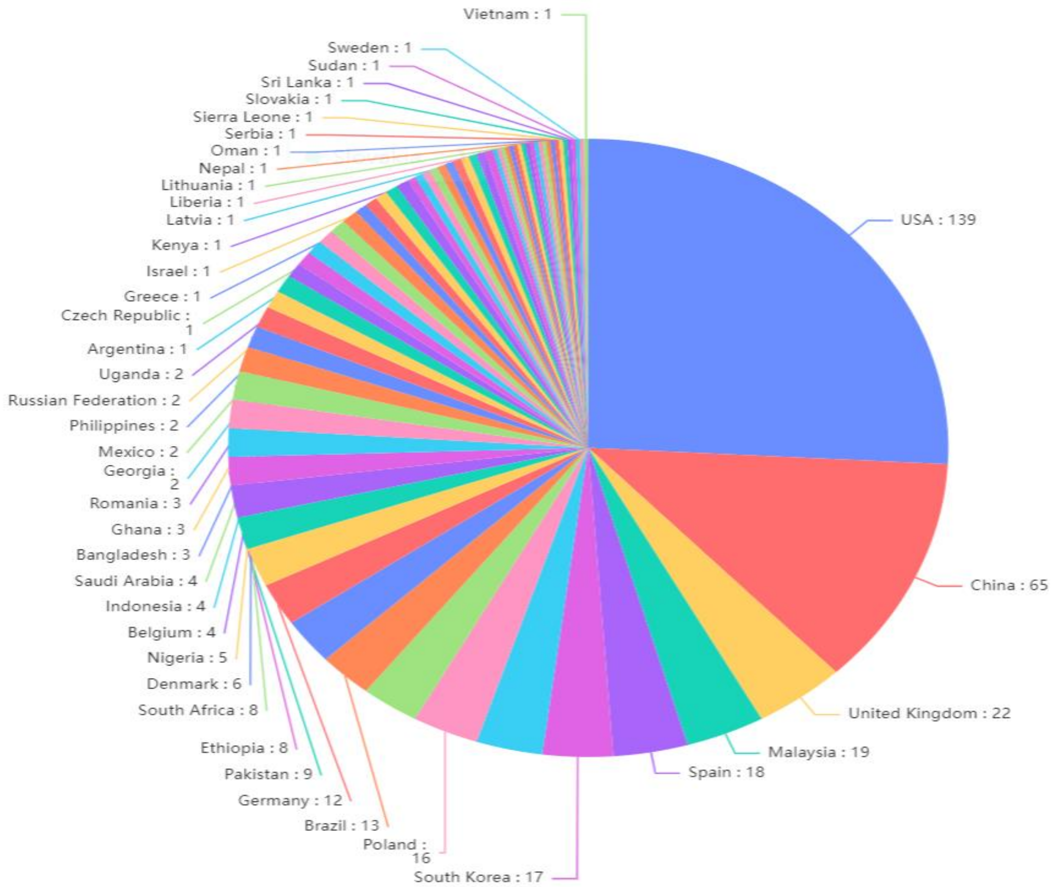

Figure 1.
Main Contributing Countries.

As an essential means of studying technological development and innovation, patent analysis can reveal the path and direction of technological evolution [5]. By analyzing patent data, it is possible to understand the R&D priorities and innovations of companies and research institutes in PPE and identify emerging technologies with potential. Milad and Rosa [6] explored the current state of intelligent wearable technology and market direction through a patent analysis in 2017 [7]. This study aims to systematically investigate the current technological status, development opportunities, and future trends of PPE at construction sites through the method of patent analysis. Through in-depth mining and analysis of patent data, we will sort out the major technological innovation points and market dynamics in the field of PPE and reveal the driving forces and challenges behind technological development. The results of the study will not only provide theoretical support for the R&D and improvement of PPE and a reference for the innovative development of the construction industry.

2. Methodology

We retrieved worldwide patent applications for Smart PPE using the validated search query proposed by Spear [8]. The study's specific research methods and steps are as follows: (1) Data Collection: Firstly, Derwent Innovation is selected as a data source, such as Derwent Innovation, Google Patents, and PatSnap. The specific Boolean search expression was as follows: ctb=(“personal protective equipment*") or ctb=(“PPE*") or and ctb=(“construction*") and ay>=(1992) and ay<=(2024). (2) Data Cleaning and Screening: The preliminary searched patent data are cleaned and screened to remove patents unrelated to the research topic. The abstract, claims, and technical solutions are examined for each patent to ensure they relate to construction site PPE. Finally, a high-quality patent data set is formed for subsequent analysis. The result was 284 searched records. (3) Patent Classification and Statistical Analysis: Classify the screened patents by different types of PPE (e.g., helmets, protective glasses, safety shoes, etc.). At the same time, statistical analysis of the number of patents is conducted to understand the technological development of each type of PPE in different periods. In addition, the leading patent holders are analyzed to understand which companies and research institutes have a leading position in the field. (4) Technology Trend Analysis: Reveal the technology development trend in PPE through patent text mining and technology hotspot analysis. We extract key technical terms and topics in patent documents through content analysis and identify the main technical innovations and research hotspots. (5) Analysis of opportunities and challenges: Analyze potential opportunities and challenges in PPE, considering market demand and technology development trends. For example, to explore the application prospects of intelligent wearable devices and IoT technologies in PPE, as well as the research and development of new materials to enhance the performance of PPE.

3. Results

Table 1 outlines the diverse applications of innovative PPE in enhancing safety and operational efficiency on construction sites and the common challenges associated with their adoption and use.

Table 1.
Common Smart PPE in Construction Sites.

PPE	Function	Limitations
Smart Helmets	Real-time monitoring of worker's health and environment; GPS tracking for location and safety; Communication with team members	High cost; Battery life limitations; Potential discomfort due to added weight
Smart Glasses	Augmented reality (AR) for overlaying instructions and schematics; Hands-free communication; Real-time hazard identification	Expensive; Limited battery life; Can be distracting or cumbersome for users.
Smart Safety Vests	Monitoring worker’s vital signs (heart rate, temperature); GPS tracking and fall detection; Integration with site management systems	High initial cost; Data privacy concerns; Requires regular maintenance and calibration.
Smart Gloves	Enhanced grip and dexterity with haptic feedback; Monitoring hand movements to ensure proper technique; Detection of hazardous substances	Durability issues; Potential discomfort; Battery life and maintenance requirements
Smart Boots	Fall and slip detection; Monitoring pressure and impact to prevent injuries; GPS tracking.	High cost; Battery life constraints; Potentially uncomfortable over long periods

3.1. Smart Helmets

Intelligent helmets have entered the practical application stage from the conceptual stage. What is currently known as a smart helmet, in other words, is the integration of a standard helmet with various sensors, such as an infrared sensor, a DS18B20 temperature sensor, an acoustic sensor, an MQ-3 gas sensor and an MQ-135 smoke sensor, all of which are used to detect different parameters of the worker, such as drowsiness, body temperature, acoustic sound, gas leakage, and smoke concentration [9]. Some manufacturers have already launched intelligent helmets with various functions, such as smart helmets with night vision functions; there are also intelligent helmets with voice recognition and smart navigation functions, which can provide more convenient and practical functions. For example, Aliyev et al. presented a connected smart helmet platform, HeadgearX, with ten sensors, visual and haptic feedback mechanisms, and Bluetooth connectivity. Construction project supervisors can monitor the real-time status of all on-site personnel via a smartphone that communicates with the individual helmet via its wireless network [10]. Secondly, the research on intelligent helmets also involves communication, wireless charging, and lightweight technology. Abbasianja et al., on the other hand, developed helmets for real-time monitoring of the hearing health of construction site workers using Internet of Things

(IoT) conceptual architecture and KY-037 audio sensors [11]. The practicality of intelligent helmets is also getting more and more attention. Using sensors and algorithms, smart helmets can provide practical functions such as human health monitoring, traffic safety warnings, environmental information prompts, etc. The training dataset for the smart helmet developed by Israel consists of 11,755 samples and 12 different scenarios, which is a huge amount of data [12]. However, intelligent helmet research also involves some ethical and social issues. For example, smart helmets may include personal privacy and data security issues, which require formulating and improving relevant regulations and standards. Meanwhile, the design and use of intelligent helmets also need to consider factors such as the wearer's physical condition and exercise habits to ensure the safety and effectiveness of the product.

3.2. Smart Glasses

The current state of research in the construction of smart glasses focuses on improving work efficiency and safety on the job site. Combining augmented reality (AR) technology and building information modeling (BIM), these smart glasses can provide real-time construction drawings, 3D models, and work instructions, reducing reliance on paper documents and helping workers locate and accurately install building components. Smart glasses receive signals sent by Bluetooth beacons attached to heavy equipment or vehicles at a distance determined by signal strength. When the distance is close, a visual alert is displayed to the wearer. The Bluetooth beacon's Media Access Control address provides information about the approaching device or vehicle, which is displayed to the wearer so they can react appropriately [13]. In addition, the research explores the prevention of safety incidents by monitoring the construction site environment and worker operations through built-in cameras and sensors. Baek and Choi developed smart glasses to receive BLE signals from Bluetooth beacons and provide visual proximity alerts to pedestrians. The average BLE signal recognition distance for the smart glasses was approximately 37.4 meters when the excavator approached from the front of the worker and 19.4 meters when the excavator came from the rear of the worker [13]. The durability, comfort, and battery life of construction smart glasses for long wear periods are also vital research directions. Despite some technological advances, the functionality of smart glasses developed through the Android API still needs to be expanded. Other topics of interest include performance enhancement and lightweight, design and interface implementation, battery life extension, and safety improvements [14].

3.3. Smart Safety Vests

The current research on construction bright safety vests focuses on improving site safety and work efficiency. Bright safety vests are usually equipped with sensors such as GPS, accelerometers, gyroscopes, and heart rate monitors, which can monitor the position, posture, and physiological conditions of workers in real time and detect and alert potential hazards on time, such as falls, overexertion or intrusion in dangerous areas. In addition, the vests can be connected to site management systems for remote monitoring and data analysis to optimize safety management and emergency response. Research is also working to improve sensor accuracy, vest comfort, durability, and extend battery life. Rajendran, et al. [15] successfully retrofitted the traditional safety vest by adding a simple metal detector kit that will signal a warning when there is a metal hazard in the vicinity of a worker in the field Rajendran, et al. [15]. Guo, et al. [16] developed a new hybrid cooling vest to combat heat stress in the construction industry. The results of environmental chamber tests showed that subjects wearing the novel cooling vest showed significant improvements in coolness, dryness, comfort and physical recovery. While these technologies have been applied in several pilot projects, the waterproofing capability of many of the current intelligent vests is inadequate for more extreme field work such as offshore and underground work. There is also a limited detection range and a lack of online tracking systems for real-time monitoring.

3.4. Smart Gloves

The current state of research on construction bright gloves focuses on enhancing the precision and safety of site operations. These gloves, equipped with sensors, RFID chips, and wireless communication modules, can detect workers' hand movements, forces, and environmental conditions, providing real-time feedback and guidance to reduce operational errors. Mansoor presented the development of a sensor-based smart construction glove that uses a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer to measure the orientation of the hand with the help of quaternions, and a bending sensor to measure the strength of finger flexion [17]. The intelligent gloves can also record quality control and person-hour management workflow data. Liu et al., in 2021, made an intelligent glove prototype by attaching ultra-thin, sensitive, and stretchable ZNS-01 sensors to the surface of an ordinary glove [18]. They built a data acquisition system to enable limited data collection of human hands touching surfaces such as tabletops, wood, plastics, steel, and paper. Wang and Song designed a pair of PZT-enabled Smart Gloves (SGs) and wore them on a robotic manipulator that could grip the scaffolding and determine the integrity of the scaffolding by analyzing signals through an entropy-based Damage Index (DI) [19]. Research is also exploring the durability and comfort of the gloves, as well as their performance stability in various environments. While bright gloves have performed well in several experimental projects, they still face challenges in cost, data privacy, and technology integration in large-scale practical applications.

3.5. Smart Boots

Current research on the construction of bright boots is dedicated to improving the safety and comfort of site workers. Equipped with various sensors such as pressure sensors, accelerometers, and gyroscopes, these intelligent boots can monitor a worker's gait, posture, and working environment in real time to provide early warning of potentially hazardous situations such as unstable ground or excessive fatigue. Lee and Son [20] proposed a prototype system to track the weight of heavy loads carried by construction workers by developing smart safety shoes with FSR (Force Sensitive Resistor) sensors; the proposed weight tracking system has a significant average accuracy of 90.2% in classifying the weight of each experimenter [20]. In addition, intelligent boots can communicate with other devices or systems, such as innovative safety vests or worksite management systems, for more comprehensive safety monitoring and data analysis. Chu, et al. [21] developed a fully recyclable, green, fire-resistant friction electro elastomer through geometrically synergistic fillers and applied it in smart firefighting boots. However, the durability of sensors, the durability of batteries, and the ease of wearing safety footwear in various construction work environments continue to plague the development of intelligent safety boots. Secondly, the different physical conditions of construction workers, the grounding conditions of the shoes, and the use of other types of sensors also need to be validated and analyzed in more diverse environments.

4. Discussion

Current personal protective equipment (PPE) for construction sites faces various challenges, including the following: (1) Comfort and wearability: PPE needs to provide adequate protection while ensuring that it is comfortable for workers to wear for long periods. However, many existing PPEs fall short in weight, breathability, and flexibility, making workers reluctant to wear them in hot or heavy work environments. Uncomfortable equipment may cause workers to operate in violation of the law or be unwilling to wear it, thereby increasing the risk of injury. (2) Technology Integration and Intelligence: Despite the massive potential for intelligent PPE, it faces the challenge of technology integration in practical applications. A common explanation of PPE-based health is that images from the field are constantly uploaded to the cloud for analysis. This centralized architecture requires a significant amount of network bandwidth to transmit the video feed over what must be a reliable Internet connection, as network outages can disrupt service. For example, embedding sensors and communication modules into traditional protective equipment requires overcoming technology compatibility issues, data transmission stability, and battery life. Inadequate technology integration can lead to insufficient reliability and practicality of innovative PPE to effectively enhance site safety. (3) Material and durability: PPE needs to have characteristics such as high strength, abrasion resistance, and puncture resistance, but how to balance cost and performance in material selection and manufacturing process is a significant challenge. Existing materials sometimes cannot fully meet the demanding requirements of the site environment. Unadorable equipment is prone to damage during use, reducing the effectiveness of protection and increasing the frequency and cost of replacement. (4) Standardization and Compliance There are differences in standards and regulations for PPE in different countries and regions, and companies need to consider compliance with various standards during the design and production process. In addition, the application of new technologies and materials may also face the problem of updated standards and regulatory lag. Standardization and compliance issues may lead to barriers to market entry for products, affecting an enterprise's international competitiveness and market coverage. (5) Economic cost and popularity: High-performance PPE is expensive to develop and produce, especially for intelligent and high-tech equipment. This puts economic pressure on small and medium-sized construction companies to procure and popularize high-quality PPE. The high cost limits the popularity of PPE, preventing some construction sites from being fully equipped with advanced protective equipment and affecting the overall safety level of workers. (6) Training and Awareness: Even with suitable PPE, proper use and maintenance by workers are vital to ensuring its effectiveness. However, many sites have not invested enough in worker training and safety awareness, significantly reducing the protective effect of PPE.

The following strategies can be adopted to improve the development of personal protective equipment (PPE) for construction sites: (1) Enhance comfort and wearability. Firstly, ergonomic design concepts are adopted to ensure the comfort and flexibility of PPE under different working conditions. Second, develop and apply lightweight and high-strength materials, such as carbon fiber and advanced polymers, to reduce the weight of PPE. Thankfully, the latest advances in stretchable and textile-based electronics, fueled by nanotechnology, offer almost every conceivable solution to the unmet needs identified by PPE users and expert advisory groups [22]. Finally, PPE's breathability and heat dissipation can be improved by designing protective clothing and helmet ventilation holes. (2) Promote intelligence and technology integration. Firstly, a modular design should be adopted to make intelligent components easy to replace and upgrade and enhance the flexibility and maintainability of equipment. Second, advanced wireless communication technologies, such as

5G and power-wide Wide Area Networks (LPWAN), should be integrated to ensure stability and real-time data transmission. Finally, low-power electronic components and efficient power management systems should be developed to extend the battery life of intelligent PPEs. (3) Improve materials and manufacturing processes. First, invest in developing new materials, such as nanomaterials, self-repairing materials, and intelligent materials, to improve PPE's protective performance and durability. Second, advanced technologies such as 3D printing and additive manufacturing should be adopted to customize PPE precisely to suit the needs of different workers and working environments. Finally, strict durability testing standards and methods must be established to ensure PPE's long-term stability and reliability under harsh working conditions. (4) Strengthen standardization and compliance. First, promote the docking and unifying global PPE standards to reduce barriers to international market access. Secondly, establish a dynamic standard update mechanism to promptly incorporate the application requirements of new technologies and materials, ensuring that PPE always complies with the latest safety specifications. Finally, improve the PPE certification system and introduce third-party independent testing and certification organizations to enhance product credibility and safety. (5) Reduce Costs & Enhance Popularity. First, reduce the unit cost of PPE through large-scale production to make high-performance devices more affordable. Second, the government provides subsidies and tax incentives to encourage enterprises to research, develop, and purchase advanced PPE. Lastly, enterprises are encouraged to cooperate with scientific research institutes to develop innovative PPE and share R&D costs and risks jointly. (6) Enhance training and awareness. Conduct regular safety training to enhance workers' awareness and skills in adequately using and maintaining PPE. Yang, et al. [23] present a PPE-Tool pairing system for on-site construction safety. Through wear detection. The system ensures that users are adequately equipped with all necessary PPE before using dangerous construction hand tools. This protective system consists of wear sensors, batteries, and a Wi-Fi module; each tool has a buzzer, a vibration motor, and a Wi-Fi module [23]. (7) Strengthen information management and technology updating. Firstly, establish a PPE technology information sharing platform to release the latest technological developments and market trends promptly to help enterprises stay at the forefront of technology. Second, through the extensive data analysis and feedback mechanism, real-time monitoring of PPE usage, identifying problems and making timely improvements. Finally, a continuous innovation mechanism is established to encourage enterprises to continuously explore new technologies, materials and designs to maintain product competitiveness.

5. Conclusion

Worker safety remains a serious issue as accidents and deaths on the job are very common, especially on construction sites. This study systematically uses patent analysis to examine the current state of the art, development opportunities, and future trends of personal protective equipment (PPE) for construction sites. It was found that the current construction site PPE faces many challenges in terms of comfort, intelligence, material durability, standardization, economic cost, and training in use. To address these issues, this study proposes a variety of improvement strategies, including enhancing comfort and wearability, promoting intelligence and technology integration, improving materials and manufacturing processes, reinforcing standardization and compliance, lowering costs and increasing penetration, improving training and awareness, and strengthening information management and technology updates. Specifically, the adoption of ergonomic design and lightweight materials can significantly improve the comfort and wearability of PPE; the integration of low-power electronic components and wireless communication technology can help promote intelligence and technology integration of PPE; and the development of new materials and the application of advanced manufacturing technology will enhance the durability and performance of PPE. Enhanced standardization and compliance can ensure the applicability and reliability of PPE globally. At the same time, the cost of PPE can be effectively reduced, and its penetration rate increased through large-scale production and government support. In addition, regular safety training and building a safety culture are crucial to enhancing workers' awareness and skills in using PPE. Establishing an information-sharing platform and a continuous innovation mechanism will help companies stay at the forefront of technology and continuously improve and innovate PPE. The construction industry can utilize cloud computing services in conjunction with smart PPE to take advantage of the latest advances in new technology avenues to enhance building safety management. It is worth noting that this study also has some limitations. The choice of patents to measure technological progress in this study is imperfect because not all inventions eventually go through the patent application process. Secondly, the DI database does not comprehensively cover global patent applications. Future research suggests cross-validation with other patent databases such as Google Patents, Espacenet, USPTO Web Patent Database, PQAI, Patentscope by WIPO, WIPO's INSPIRE, and Lens.org.

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