Development of Smart and Modular Electrical Hazard (EH)-Rated Boots for Enhanced Protection, Monitoring, and Sustainability

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Development of Smart and Modular Electrical Hazard (EH)-Rated

Boots for Enhanced Protection, Monitoring, and Sustainability

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Abstract

EH-rated boots offer a critical safety measure for workers operating in an energized electrical system environment; however, the current EH-rated boots have no real-time feedback with respect to the electrical hazards and experience reduced service life due to quick wear of outsole. This paper presents the next generation Safety Footwear System based on modularity, smart sensing and technically engineered rubber sole.

A crucial technological element is the creation of an EH Shoe, based on real time sensing, constructed using non-conductive elastomeric compounds characterized by high dielectric strength, low surface conductivity and enhanced resistance to abrasion, ensuring compliance with existing EH standards and long-term safety. Micro-sensors integrated in nonconductive modules to observe stress development, thermal rise and shock impact are implemented for intelligent protection improvement. These sensors include real-time warning capability for proactive risk control in electrical working environments.

The methodology includes CAD based design, FEA to optimization, fabrication of insulating rubber sole with incorporated smart sensors, laboratory testing for dielectric strength as well as durability and pilot field trails. The anticipated result is a prototype that has been validated to show superior protection, durability/

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sustainability, and perceived effectiveness. This work aims to impact next generation safety standards and introduce a new culture in smart modular EH-rated footwear.

Keywords: Electrical Hazard (EH) Footwear, Rubber Outsole Design, Dielectric Strength, Non-Conductive Materials, Modular Safety Footwear, Smart Sensing, Occupational Safety, Footwear Sustainability, SensorIntegrated Boots.

1. Introduction

Safety at work is still a big worry in all industries, and foot and lower extremity injuries make up a large part of workplace accidents. Traditional safety footwear offers basic protection against mechanical and electrical hazards, but it is passive equipment that doesn’t do anything to stop accidents or give real-time safety information. With the rise of Industry 4.0 technologies like the Internet of Things (IoT), artificial intelligence (AI), and advanced materials science, safety footwear can now be turned into smart, adaptable systems that actively help keep the workplace safe [1]. This research looks at the design, methods, and expected results of next-generation safety footwear systems that combine three main ideas: modular design architecture, smart sensing capabilities, and technically developed rubber sole technology. With the modular approach, you may customize it for different industrial uses and worker needs. Smart sensor technologies, on the other hand, keep an eye on worker

movements, ambient conditions, and the performance of the shoes at all times. Advanced designed rubber soles use tribological principles to improve slip resistance, durability, and electrical hazard (EH) protection. This addresses the main causes of workplace accidents to the feet.

The coming together of these technologies marks a big change in the way we think about safety footwear, going from reactive protection to proactive risk reduction. Nextgeneration safety footwear can find potential dangers

before they happen by using real-time data collection, AIdriven analytics, and cloud-based monitoring systems. It can also warn workers and supervisors about dangerous situations and give them useful information to help them keep their safety up to date [2], [3]. This change is in line with bigger trends in the development of smart PPE, where wearable technologies are becoming more and more important parts of whole workplace safety management systems [4, 5].

The expected effects of these systems go beyond just protecting individual workers. They also include improving the safety culture of the business, making sure that rules are followed, and changing industry-wide standards. The use of sensing technologies and data analytics together can lower the number of accidents, speed up emergency response times, and create a culture of proactive safety management, as shown by related smart PPE applications [6], [7]. For safety footwear, the combination of modular design, smart sensing, and engineered materials is expected to set new standards for EH-rated footwear performance and change what people expect from the next generation of industrial safety equipment.

1.1 Evolution of Safety Footwear

Safety footwear has come a long way from simple leather boots with steel toe caps. Now, they include advanced protective systems that use composite materials, ergonomic design, and specific sole technologies. Traditional safety shoe requirements mostly look at how well they protect against impacts, compression, punctures, and electrical hazards. But these traditional methods don’t provide us a clear picture of how things are really being

used, how they’re wearing down, or new dangers that are coming up. They are more reactive than proactive when it comes to safety. As occupational safety standards have gotten more complex, the flaws in traditional PPE have become more obvious. Research on smart PPE in construction and industrial settings indicates that conventional equipment frequently fails to avert accidents due to incorrect usage, insufficient monitoring, and the absence of real-time hazard identification [1]. This acknowledgment has propelled research towards intelligent personal protective equipment (PPE) systems capable of actively monitoring conditions, identifying anomalies, and delivering prompt feedback to workers and safety management.

1.2 Smart PPE and Industry 4.0

Adding smart technology to PPE is a natural next step for Industry 4.0, which focuses on connection, data-driven decision-making, and intelligent automation. Recent research shows that smart PPE development has come a long way for several types of equipment. For example, smart helmets, wearable sensors, and connected safety systems all have a lot of potential to make workplaces safer [1], [2], [3], [4], [5].

Smart personal protective equipment (PPE) systems usually have more than one type of sensor that can keep an eye on things like temperature, humidity, gas concentrations, and particulate matter in the environment, as well as the worker’s heart rate, body temperature, and movement patterns. They can also keep an eye on the equipment’s status, such as how well it is being worn, whether it has been hit, and where it is located [7, 8, 10, 12]. These systems use IoT connectivity to send data to central monitoring platforms, where AI algorithms look for patterns, find hazards, and send alarms [5, 11, 16]. Studies show that these kinds of systems can find hazards with a high level of accuracy. Some implementations have even reported over 90% accuracy in risk identification and classification [5, 12].

The effectiveness of smart helmets and wearable safety gadgets establishes a robust basis for the enhancement

of analogous features in safety footwear. Smart helmets have shown that it is possible to combine many sensors, wireless connection, and AI-driven analytics into wearable PPE while still keeping users comfortable and making it useful for work [4], [5], [10], [12], [13]. These examples help shape the design of next-generation safety footwear systems. They show that similar technology integration can be done in devices that are worn on the feet.

1.3 Modular Design Principles

Modular design concepts provide substantial benefits for safety footwear systems by facilitating customization, upgradability, and adaptation to various industrial applications. With a modular architecture, you can choose and combine different parts including sensor modules, sole configurations, upper materials, and power systems based on the needs of your workplace, the risks involved, and the preferences of your workers. This is distinct from standard safety shoes that suit everyone. Instead, it gives each industry, from construction and manufacturing to mining and electrical utilities, the freedom to meet their own needs.

The idea of modularity goes beyond only physical parts to incorporate software and data analytics tools as well. Different sensor packages can be used depending on the type of hazard: for example, electrical workers may need better EH-rating monitoring and ground fault detection, while construction workers may need better fall detection and gait analysis. In manufacturing settings, fatigue monitoring and ergonomic assessment may be

more important, while in mining settings, environmental hazard identification and location tracking may be more important [8], [12]. This flexibility lets companies get the most out of their safety footwear expenditures while still using standard systems for data integration and analysis.

Research on smart wearable insoles shows that it is possible to use modular sensors in shoes. Research indicates that insole-based systems may proficiently execute human activity recognition, gesture estimation, fatigue detection, and slip/trip/fall hazard identification utilizing machine learning models with accuracies between

91% and 96% [17]. These results confirm the technological feasibility of integrating advanced sensing and processing functionalities into footwear designs, hence endorsing the practicality of modular smart safety footwear systems.

1.3.1 Upper Assembly

The upper part of the shoe keeps your feet comfortable, safe, and connected to the modular base. You can choose from a variety of upper designs according on the weather, the types of hazards present, and the preferences of the workers. For example, you can choose lightweight, breathable designs for indoor manufacturing or heavy-duty, waterproof designs for outdoor and mining operations.

2.3.2 Electrical Hazard Sensors

These sensors check for electrical conductivity, ground continuity, and possible voltage exposure to make sure the EH rating is correct and to find any electrical protection that isn't working. These sensors check electrical hazard protection in real time and let workers and managers know when footwear no longer satisfies EH-rating standards because it has been worn, damaged, or contaminated.

1.4 Engineered Rubber Sole Technology

The designed rubber sole is a major step forward in safety footwear for the next generation. It uses modern tribological principles, materials science, and protection against electrical hazards. Based on studies on slip-resistant surfaces and advanced materials [29], the designed sole has several functional layers that work together:

Tribological Surface Layer : The outermost layer uses innovative rubber compounds with surface textures that are tailored to get the highest coefficient of friction (COF) in a wide range of surface conditions. Studies show that surfaces that are designed correctly can reach COF values of 0.65 to 0.85 in wet conditions, which can cut down on slipand-fall accidents by 15 to 25% [29]. The surface has microscale and nanoscale characteristics that make it more hydrophobic and help it lock into place with floor surfaces, which are the main causes of slip-related accidents.

Electrical Hazard Protection Layer: A unique dielectric layer protects against electrical hazards and meets or exceeds the ASTM F2413 EH-rating criteria. This layer uses innovative rubber formulations with controlled electrical resistance capabilities to defend against electrical shock threats up to certain voltage levels. Embedded sensors keep an eye on the electrical properties of this layer all the time. This lets users check the EHrating integrity in real time and warns them if anything goes wrong that could lower protection.

Structural Support Layer: An intermediate layer gives mechanical support, keeps things from getting punctured, and absorbs energy to defend against impact and compression risks. This layer may include composite materials, tailored foams, or sophisticated polymers to get the best balance between protection, weight, and flexibility.

Sensor Integration Layer: The Sensor Integration Layer is a separate layer that holds embedded sensors, wiring, and electronic parts. It protects them from mechanical stress, moisture, and other things that could damage them. This layer makes sure that the sensors are reliable and last a long time while keeping the safety footwear's mechanical qualities.

Comfort and Ergonomic Layer: The innermost layer provides cushioning, moisture management, and ergonomic support to keep workers comfortable for long periods of time. This layer might have pressure-mapping sensors that keep track of how the force is spread out and give feedback on how to improve the fit and reduce fatigue.

The multi-layer sole design lets you optimize each functional requirement separately while still keeping the whole system working together. Advanced production methods, like as 3D printing and multi-material molding, make it possible to change the qualities of the sole to fit certain uses and worker needs [23].

2. Methodology and Implementation Approach

2.1 System Development Framework

The creation of next-generation safety footwear systems is based on a systematic approach that is based on

successful smart PPE implementations [4], [5], [10], [12], and [16]. There are various steps in the framework:

Conceptual Design: Creating the system's architecture, defining the specifications for each part, and figuring out how to put everything together. This stage sets up the modular structure, picks the main technologies, and defines the interfaces between components. Conceptual designs are improved throughout time based on feasibility studies and feedback from stakeholders.

Prototype Development: Making working prototypes that include sensors, electronics, designed soles, and communication systems. Rapid prototyping and modular assembly are used in prototype development so that different configurations can be quickly tested and iterated [23]. Different application scenarios and hazard profiles are covered by different prototype variants.

Controlled testing of prototype systems in a lab to check the accuracy of sensors, the performance of algorithms, the amount of power they use, the dependability of connectivity, and the mechanical qualities. There are conventional safety methods for testing safety footwear in the lab, and there are also particular tests for smart features. Testing involves calibrating sensors, checking the fall detection algorithm, simulating exposure to different environments, and checking for electrical hazards [4], [10], [12], and [16].

Field Trials: Putting prototype systems to the test in realworld work settings to see how well they work, how well users accept them, and how reliable they are in operation. Field trials necessitate collaboration with industry partners from many industries to assess system performance under a range of settings [4], [16]. Trials gather both quantitative performance statistics and qualitative user comments to help improve the design.

Validation and Certification: Full validation against safety standards and regulatory criteria, such as ASTM F2413 for protective footwear and the standards that apply to electronic equipment in dangerous locations. Certification processes make ensuring that EH-rating criteria and other safety standards are met.

Integration Design : Creating mechanical and electrical integration plans that keep sensors safe from environmental dangers while still giving accurate readings. Integration design deals with problems including moisture getting in, mechanical shock, severe temperatures, and electromagnetic interference. Optimizing sensor location makes sure that measurements are precise while having the least effect on the comfort and performance of shoes.

3. Testing and Validation Protocols

To ensure compliance with Electrical Hazard (EH) safety footwear requirements and to evaluate the mechanical, physical, and functional performance of the developed shoe, comprehensive testing was carried out on both the upper and sole materials in accordance with relevant ISO, SATRA, and ASTM standards. The upper material, buffalo split leather, was evaluated for its suitability in safety footwear applications through tensile strength and elongation testing (ISO 3376) to assess strength and flexibility, tear strength testing (ISO 3377-2) to determine resistance to propagation of cuts, and thickness measurement (ISO 2589) to ensure uniformity and durability. Flex resistance was examined using the Bally flex method (ISO 5402-1) under dry conditions to simulate repeated walking cycles, while grain/surface strength was assessed through ball burst testing (ISO 3379) to evaluate resistance to cracking during lasting and prolonged use. Comfort-related properties were assessed through water vapour permeability testing (ISO 14268) and water

S. No Test Guideline Value

1 Upper Leather Tensile Strength 15 N/mm2 2 Tear strength, N (Shoe upper) 100 N 3 Stitch tear strength, N/mm 80 N/mm 4 Flexing resistance (Vamp) - Dry 500000 flexes, no crack 5 Slip resistance - Dry 0.3 6 Slip resistance - Wet 0.3 7 Hardness, IRHD 50-70 8 Oil resistance Maximum 12% 9 Sole Electrical Resistance >1*106 Ohm 10 Electrical Insulation (EH Test) <1.0 mA

absorption testing (ISO 5403-1) to understand breathability and moisture resistance of the leather upper.

The outsole material, Styrene-Butadiene Rubber (SBR), was subjected to hardness testing (ISO 7619-1) to achieve an optimal balance between comfort and wear resistance. Tensile strength and elongation at break were measured as per ISO 37 to assess rubber elasticity and durability. Abrasion resistance, a critical parameter governing sole life, was evaluated using the DIN abrasion method (ISO 4649), while flex resistance was assessed according to ISO 17707 to ensure crack-free performance under repeated bending. Slip resistance testing was conducted as per ISO 13287 on ceramic and steel surfaces to evaluate anti-slip performance in industrial environments. Density testing (ISO 2781) was carried out to control sole weight and material consistency.

Finally, EH-specific performance of the finished footwear was validated through electrical insulation testing in accordance with ASTM F2413, wherein the shoe was subjected to 18,000 V at 60 Hz for one minute under dry

conditions, ensuring leakage current remained within permissible limits and no dielectric breakdown occurred. Electrical resistance of the sole was further evaluated as per ASTM F2412 to confirm adequate insulation characteristics of the SBR outsole. These comprehensive evaluations collectively ensure that the developed EH safety shoe meets the mechanical, comfort, durability, and electrical safety requirements for high-risk electrical work environments.

4. Conclusion

This study created a next-generation Safety Footwear System for electrical hazard (EH) conditions. It fixed the major problems with regular EH-rated boots, which were that they didn't give real-time hazard input and their outsoles wore out quickly because of abrasion. Using a systematic approach that included CAD-based design, finite element analysis (FEA) for optimization, making insulating rubber soles with built-in micro-sensors, and rigorous lab testing for dielectric strength and pilot field trials, the prototype showed better electrical insulation (high dielectric strength and low surface conductivity), longer life, and proactive monitoring of stress, thermal rise, and shock impacts. While still following established standards like ASTM F2413, modular, non-conductive sensor modules were added that allow for real-time warnings. This changed passive EH protection into an intelligent, responsive system.

This EH Shoe is the best example of smart modular footwear for energized work settings because of its new technologies, such as technically created non-conductive elastomeric compounds that are optimized for abrasion resistance and sensor integration. Expected results from validation include a longer service life, less risk exposure thanks to proactive alarms, and a better sense of worker safety, with the possibility of sustainability advantages through data-driven maintenance. This work sets the stage for changing future EH safety standards by making continuous monitoring and modularity key needs.

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