Precautions and Prevention for Sustainability Design & Development Smart Analytic Footwear for Ergonomics & Safe Fatigue Tracking for Employee Protection (SAFE - STEP) Development of Virtual Environment with Dynamic Simulation of Colour,

Conference: 13th AICLST, Kolkata, 6–8 March 2026

Paper reference: TF-76/O

Printed pages: 274–279

Source: *Leather 2050: Challenges & Opportunities*, ILTA (2026)

Design & Development Smart Analytic Footwear for Ergonomics & Safe

Fatigue Tracking for Employee Protection (SAFE - STEP)

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Ref. No. TF-76/O

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Abstract

Occupational fatigue in industrial workers is still a major problem, leading to loss of productivity, risk of accidents and long-term musculoskeletal disorders. Conventional methods for fatigue measurement are based on subjective reports or laboratory equipment and are not suitable for real-time applications in the field. We propose the development of a Smart Footwear with pressure-sensing insoles (customized) that incorporates intelligent analytics, which can autonomously monitor for fatigue continuously during work-days in industrial environments. The specific aim is to develop an AI-based fatigue-prediction model with gait changes, Center of Pressure (COP) and plantar pressure distribution patterns, design a preventive safety shoe intervention that can generate early warning.

The approach involves the fabrication of wearable flexible pressure sensor array based on conductive fiber to implement a safety shoe with wireless communication (BLE), and a real-time data pipeline for fatigue prediction using machine learning. Fieldassessment prior model fabrication and field testing with industrial workers will be assisted by subjective fatigue assessment scales and bio-mechanical validations. Anticipated outcomes will be the determination of fatigue-specific gait biomarkers, the creation of predictive algorithms for early detection of fatigue, and a hardware prototype for real-time ergonomic risk feedback.

This research is valuable for us by shortening the period taken to move from traditional shoes to

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technology-supported smart safety shoes providing additional functions, thus improving global competitiveness. The proposed solution supports worker wellbeing, reduces occupational hazards, and opens new opportunities for Industry-aligned smart PPE innovation and commercialization within the Indian leather and safety-footwear market.

Keywords: Smart safety footwear, occupational fatigue, plantar pressure, Centre of Pressure (COP), machine learning, workplace safety.

2. Introduction

Fatigue among industrial workers has become a significant factor in musculoskeletal diseases, diminished productivity, and workplace accidents. In jobs that involve standing for long periods of time or walking the same distance over and over again, fatigue builds up over time and often is not noticed until performance drops or an injury happens. Surveys, physiological sensors, and laboratory-based motion capture are some of the traditional ways to measure fatigue. However, they are either subjective, disruptive, or not practicable for use in real-world working environments.

Recent trends & advancements in wearable technology have made it possible to keep an eye on health and safety all the time. Footwear is a unique and underused platform for wearables since the foot is the main connection between the body and the working environment. It is recognized that there will be a small change in the Center of Pressure (COP), the stability of the stance, distribution of plantar pressure and the symmetry of the gait, comes before reported exhaustion/fatigue.

Fig. 1: Change in the Stabilometry (Body Center of Pressure) before and after fatigue.

Even though smart shoes are becoming more popular, the latest technologies primarily track the physical activity, assess gait in a clinical setting, or measure sports performance. Their use for predicting occupational fatigue or exhaustion is still restricted, especially in the industrial environments where safety is very crucial and resources are limited. There is a strong need for a smart shoe system that is easy to use and it will be able to identify the fatigue early and help with preventive measures.

The integration of sensors and its technologies into footwear has gained a quick research attention due to its capability for continuous and non-invasive monitoring of biomechanics, health, and occupational safety. Recent studies report significant progress in smart footwear through the integration of plantar pressure sensors, inertial measurement units, and wireless communication for realtime gait analysis and assessing their ergonomics [1]. Deep-learning-based gait analysis has demonstrated that variations in walking patterns can reliably reflect physical fatigue and neuromuscular changes [2]. Accurate stride segmentation has been shown to be critical for fatiguerelated gait analysis, with statistically inertial-sensor-based methods [3] and pressure-sensor-based gait phase detection approaches [4], outperforming inertial-only systems. Studies incorporating footwear characteristics into machine-learning models further confirm that plantar pressure redistribution, gait symmetry degradation, and

sway variations are strongly correlated with fatigue progression during prolonged walking and standing tasks [5]. Collectively, these works establish footwear as an effective platform for biomechanical fatigue assessment.

Despite these advancements, several limitations persist in existing research. Many fatigue-monitoring approaches rely heavily on physiological signals or multiple bodymounted sensors, which restrict practical deployment in complex occupational environments [6, 7]. Subsequent studies indicate that lower-limb biomechanical data provide more reliable fatigue indicators while reducing sensor complexity [8]. Long-term industrial studies further emphasize the need for continuous, field-based monitoring to capture cumulative fatigue effects rather than short laboratory trials [9]. Although optimized pressure-sensor placement and low-complexity algorithms have proven effective for gait instability and fall detection [10, 11], fatigue-focused smart footwear systems suitable for commercial and industrial adoption remain limited. Recent developments in sensor-integrated footwear for medical applications demonstrate technical feasibility and scalability [12]; however, their application to occupational fatigue monitoring remains underexplored. This gap highlights the need for an industry-deployable, fatiguecentric smart footwear system such as SAFE-STEP, designed specifically for ergonomic monitoring and employee protection.

2. Methodology

2.1 System Architecture

The proposed SAFE-STEP system is designed as an integrated smart footwear platform for continuous biomechanical fatigue monitoring in occupational environments. The system architecture comprises a flexible plantar pressure sensor array embedded within the footwear insole to capture real-time plantar load distribution, complemented by inertial measurement unit (IMU) sensors to track gait dynamics and posture-related variations. Sensor data are acquired and processed using an embedded microcontroller unit, which facilitates synchronized data fusion and enables wireless transmission to an edge or cloud-based analytics layer. Advanced analytical models are employed to process the acquired signals for fatigue prediction, while a user-facing interface delivers fatigue alerts and ergonomic insights in an intuitive manner to support preventive interventions and workplace safety decisions.

2.2 Fatigue Measurement Framework

Fatigue in this study is defined as biomechanical deterioration resulting from prolonged occupational activity, particularly under conditions involving extended standing, walking, or repetitive load-bearing tasks. To quantify fatigue progression, multiple biomechanical parameters are

Fig. 2: Various Design Strategies of Smart Footwear.

extracted from the sensor data, including changes in plantar pressure redistribution, variability in the center of pressure (CoP), fluctuations in step time and stance phase duration, gait asymmetry indices, and trends indicating reduction in push-off force. These objective metrics are further validated against established subjective fatigue assessment tools, such as the Borg CR10 scale OR Samn– Perelli fatigue scale, to ensure physiological and perceptual consistency between sensor-derived indicators and user-reported fatigue levels.

2.3 Study Design

The study adopts a longitudinal field-based research design targeting occupational groups with elevated fatigue risk. Data collection is planned across diverse work environments, including manufacturing sectors such as automobile and capital goods industries, leather and footwear production units, security services, and construction and logistics operations. To improve contextual relevance and model robustness, individual and organizational factors such as worker experience, training level, work duration, break frequency, and shift timing are incorporated as contextual variables in the fatigue prediction framework. This approach enables the SAFESTEP system to capture cumulative fatigue effects and inter-individual variability, thereby supporting realistic, industry-oriented fatigue assessment and ergonomic intervention planning.

3. Results and Discussion

At the current stage of the project, the sensor architecture and placement strategy within the footwear system have been finalized, based on biomechanical relevance and insights from existing literature. The finalized sensor locations, covering key plantar pressure zones and gaitinformative regions, are illustrated in the proposed system figure (Fig. 3). Procurement of all required sensors, electronic components, and supporting consumables has been completed. The fabrication of the smart insock prototype is presently in progress, including sensor integration, wiring, and encapsulation, in preparation for field deployment.

Fig. 3: Placement of Sensors

Although full-scale experimental data collection is underway, the expected outcomes are derived from established biomechanical principles and findings reported in prior studies on gait and fatigue monitoring. Based on the planned longitudinal field study and fatigue modeling framework, the following fatigue-related biomechanical trends are anticipated:

 Progressive increase in Center of Pressure (CoP) drift, indicating reduced postural stability during prolonged activity Alterations in sway characteristics, reflecting neuromuscular fatigue Reduction in push-off symmetry between the left and right foot Elevated step-to-step variability in temporal and spatial gait parameters

 Premature onset of tiredness in untrained individuals and workers engaged in extended or irregular shifts

Fig. 4: In socks to be fitted with sensor

Furthermore, it is expected that intermittent rest breaks and short recovery exercises will demonstrate quantifiable fatigue recovery, evidenced by partial normalization of plantar pressure distribution and gait stability metrics. Such findings would provide objective support for ergonomically optimized break policies in industrial environments.

From a practical standpoint, preliminary user feedback and design considerations indicate high acceptance of the proposed technology, primarily due to its unobtrusive nature and seamless integration with existing safety footwear designs. This compatibility ensures minimal disruption to worker routines while enabling continuous fatigue monitoring. Overall, the anticipated results highlight the feasibility of SAFE-STEP as a scalable, industry-ready solution for ergonomic risk mitigation and employee protection.

Conclusion

This research shows that smart analytic footwear may be used to anticipate occupational fatigue. SAFE-STEP offers a new, long-lasting, and useful way to protect workers by using biomechanical insights built right into safety shoes.

Future work will focus on:

 Material optimization & improvement to reduce fatigue Footwear design optimization on fatigue reduction Adaptive feedback and haptic alerts Integration with IoT and other IR 4.0 concepts for safety dashboards Large-scale implementation and commercialization

SAFE-STEP is a big step toward the next generation of smart PPE. It combines new technology with worker safety and long-term sustainability in the workplace.

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