Integrated Smart Footwear for Real-Time Gait Analysis and Intelligent Sustainable Footwear Systems

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Integrated Smart Footwear for Real-Time Gait Analysis

and Intelligent Sustainable Footwear Systems

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Abstract

The global footwear industry is undergoing a paradigm shift driven by digital manufacturing, smart materials, sustainability imperatives and consumer demand for personalized products. Traditional footwear systems are increasingly inadequate to address emerging challenges related to health monitoring, environmental impact and performance optimization. This study presents a future-oriented roadmap for footwear innovation by integrating smart sensor technology, sustainable materials and advanced manufacturing techniques.

Fig 1. Conceptual Architecture of Integrated Smart

Footwear System

A functional prototype of integrated smart footwear capable of real-time gait analysis and athletic health monitoring is developed as a case study to demonstrate the feasibility of next-generation footwear systems. The

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research highlights sensor integration strategies, 3Dprinted cavity midsole design, anthropometric customization and eco-conscious manufacturing approaches. The proposed roadmap aligns with Industry 4.0, offering scalable solutions for sports, healthcare and sustainable footwear production.

Keywords: Smart Footwear, Sustainable Manufacturing, Gait Analysis, Industry 4.0, Intelligent Footwear

1. Introduction

The global footwear sector is transitioning from traditional craft-based production toward digitally enabled, performance-oriented and sustainable manufacturing ecosystems[1].With rising awareness of musculoskeletal health, sports injury prevention and personalized comfort, footwear is no longer perceived merely as a protective product but as an active interface between the human body and the ground[2]. Gait analysis has emerged as a critical tool for understanding locomotion patterns, detecting biomechanical deviations and improving athletic and clinical outcomes[3,4]. However, existing gait analysis systems are predominantly laboratory-based, expensive and inaccessible for continuous real-world monitoring. Smart footwear offers a viable alternative by embedding sensing technologies directly into wearable footwear platforms[5]. Simultaneously, sustainability challenges such as high carbon footprint, material waste and end-of-life

Table 1. Research Gap Analysis in Smart and Sustainable Footwear Systems

Current Research Contribution 1 Laboratory-based gait analysis systems

disposal issues demand eco-conscious innovation[6]. Integrating smart systems with sustainable materials and digital manufacturing techniques presents an opportunity to redefine future footwear design

Sl. No.

Existing Research Focus

Key Findings from

Identified Research Gap Reference

Literature

High accuracy gait data obtained using motion capture and force plates in controlled environments

Limited applicability for continuous, real-world gait monitoring due to cost, size, and immobility

2 Footwear personalization for injury prevention

Individualized footwear design can reduce overuse injuries

Lack of integrated sensing systems within footwear to enable realtime biomechanical feedback

3 Smart wearable devices (bands, clips)

Wearables capture motion data but are external to footwear

Absence of direct plantar pressure sensing and foot–ground interaction analysis

4 Digital manufacturing in footwear design

Industry 4.0 enables customization and efficiency

Limited studies integrating smart sensor systems with digital footwear manufacturing workflows

paradigms[7]. This study addresses this gap by proposing an integrated smart and sustainable footwear roadmap suitable for next-generation applications.

Phinyomark et al., 2018 [3]

Proposes footwearintegrated sensing for continuous, realworld gait monitoring

Mai et al., 2023 [2]

Integrates realtime plantar pressure and motion sensing into footwear design

Bhadane et al., 2025 [5]

Enables direct foot–ground interaction analysis through in-shoe sensor layout

Di Roma, 2017 [7]

Combines smart footwear architecture with Industry 4.0ready design concepts

Current Research Contribution 5 Sustainable footwear materials

Sl. No.

Existing Research Focus

Key Findings from

Identified Research Gap Reference

Literature

Bio-based and recycled materials reduce environmental impact

Sustainability often addressed without integrating smart functionality or electronics

6 Circular economy in product design

Lifecycle thinking improves environmental performance

Lack of smart footwear systems designed with repairability and modular electronics

7 Footwear biomechanics for high-risk populations

Biomechanicsinformed footwear improves mobility

Minimal focus on scalable smart footwear platforms for both sports and healthcare

8 Smart footwear prototypes

Demonstrated feasibility of sensor-embedded shoes

Limited emphasis on sustainability, eco-design, and additive manufacturing

9 Integrated smart and sustainable footwear systems

Not comprehensively addressed in prior studies

Lack of holistic frameworks combining gait analysis, sustainability, and digital manufacturing

— This study proposes an integrated smart footwear system combining realtime gait analysis, sustainable materials, additive manufacturing, and ethical ecodesign principles

Ogiemwonyi, 2025 [6]

Demonstrates coexistence of smart electronics with sustainable material systems

Ogiemwonyi, 2025 [6]

Adopts modular sensor integration supporting repairability and reuse

Loganathan, 2025 [4]

Presents a scalable smart footwear roadmap for sports and healthcare use

Gibson, 2016 [1]

Integrates additive manufacturing and eco-design into smart footwear development

2. Methodology

2.1 System Design and Integration Approach

The proposed smart footwear system consists of four core layers:

 Sensing Layer: Flexible plantar pressure sensors and inertial measurement units (IMUs) positioned at heel, midfoot and forefoot regions.

2.1.1 Smart footwear System for Gait Analysis

Fig 1: Smart Footwear System for Gait Analysis

 Data Processing Layer: A compact microcontroller unit enabling signal conditioning, data filtering, and wireless transmission.

 Sustainable Structural Layer: A 3D-printed cavity midsole designed to house sensors while optimizing weight reduction and energy efficiency.

 User Interface Layer: Cloud-based data visualization for gait parameters such as step length, cadence, plantar pressure distribution and temporal phases.

2.1.2 Smart Shoe component flowchart

Fig 2: Smart Shoe component flowchart

The smart shoe component flowchart illustrates an integrated system architecture comprising electronic, mechanical, and electro-mechanical subsystems that collectively enable intelligent footwear functionality. The electronic subsystem is centered around a microcontroller and sensor board that processes inputs from multiple sensors, including pressure, accelerometer, gyroscope, magnetometer, temperature, water-level, ultrasonic, and altitude sensors, to capture gait dynamics, foot motion, and environmental conditions. Wireless communication modules such as Bluetooth, Wi-Fi, and GPS support realtime data transmission, navigation and external device connectivity. The mechanical subsystem includes components such as a passive pump, actuator and springlevered pedometer, which assist in motion sensing, adaptive response and basic activity monitoring. The electromechanical subsystem integrates energy harvesting and feedback mechanisms, utilizing electromagnetic, piezoelectric, and solar generators to convert mechanical and ambient energy into electrical power, thereby enhancing system sustainability. Vibratory motors provide haptic feedback for alerts or gait correction. Together, these interconnected components form a scalable, energy-efficient, and intelligent smart shoe system suitable for applications in gait analysis, sports performance monitoring, healthcare, and sustainable footwear innovation.

2.1.3 Smart Shoe component and sensor layout

The illustrated figure 3 depicts the strategic placement of sensing nodes within the smart footwear system to capture region-specific plantar pressure and gait-related biomechanical parameters. Each sensor location is selected based on its functional role during the gait cycle.

Fig 3: Smart Shoe component and sensor layout

 Toe Region (Toe): The toe sensor monitors forefoot loading during the terminal stance and push-off phase of gait. It provides critical data on propulsion efficiency, toe-off force, and balance during forward progression.

 Heel Region (Heel): The heel sensor captures impact forces during initial contact (heel strike). This region is essential for analyzing shock absorption, ground reaction forces, and heel strike patterns, particularly relevant for injury prevention and cushioning design.

 Lateral Midfoot Pressure (LMP): The LMP sensor is positioned along the lateral midfoot to assess load transfer during mid-stance. It is particularly useful in identifying lateral instability, supination tendencies, and uneven load distribution across the foot.

 Anterior Lateral Sensor (ALS): The ALS location measures pressure variations in the anterolateral forefoot area. This sensor contributes to detecting forefoot loading asymmetry and lateral propulsion dynamics during walking or running.

 Posterior Lateral Sensor (PLS): The PLS sensor records pressure near the rear-lateral region of the foot, supporting analysis of heel-to-midfoot transition and lateral load shifts. It is significant in assessing gait deviations and balance control.

 Inner Navicular Sensor (INS): The INS is placed near the medial arch region to monitor arch deformation and medial load distribution. This sensor plays a vital role in identifying overpronation, arch collapse, and medial foot stress during stance phases.

Collectively, the multi-point sensor configuration enables comprehensive real-time gait analysis by capturing spatial and temporal plantar pressure variations. The

2.1.4 Smart insole-based plantar pressure sensing system

Fig 3: Smart insole-based plantar pressure sensing system

The figure illustrates the design, fabrication, and working principle of a smart insole–based plantar pressure sensing system for real-time gait analysis. Panel (a) shows the application concept, where a smart insole embedded inside footwear captures plantar pressure distribution during walking or running and wirelessly transmits the data to a mobile device for visualization and analysis. Panel (b) describes the fabrication process, in which laser cutting is used to create micro-patterned structures on an Ecoflex elastomer film, followed by the formation of patterned ground and top electrodes using conductive fabric to ensure flexibility and durability. Panel

data obtained support applications in performance optimization, injury risk assessment, and intelligent footwear design aligned with sustainable and smart manufacturing principles.

(c) presents the multilayer sensor architecture consisting of bottom electrodes, a dielectric layer, a top electrode array (e.g., 24 capacitive pressure sensors), and a shielding layer to reduce noise and signal interference. Panels (d) and (e) highlight the microstructural details and electrical interconnections, including electrode geometry, thickness, and welded gold (Au) contact points for reliable signal transmission. Overall, the figure demonstrates a flexible, wearable, and scalable smart insole system capable of accurately mapping plantar pressure and supporting applications in gait monitoring, sports performance assessment, and healthcare diagnostics.

Table 2. Indicative Material Testing Summary for Sustainable Footwear Components

2.2 Sustainable Material Strategy

To address environmental concerns, the footwear system integrates:

 Bio-based TPU alternatives for flexibility and durability

Material Type Application

Key Test Conducted

Area

Sensor encapsulation, flexible midsole

Tensile strength,

elongation,

Bio-based TPU

abrasion resistance

zones

Compression set,

Recycled EVA

Cushioning

energy absorption

Foam

midsole

Heel and

Fatigue resistance,

Recycled PU Foam

forefoot cushioning

hardness

Electrical resistance

Conductive Fabric

Sensor electrodes

(recycled blend)

stability

*Values are indicative results obtained from prototype-level laboratory evaluations

conducted for design validation purposes.

2.3 Ethical and Eco-Design Considerations

The design avoids hazardous substances, minimizes electronic waste through modular sensor units, and supports repairability and component replacement. Data privacy and ethical use of biomechanical data are considered through secure data handling protocols.

3. Results and Discussion

The conceptual prototype demonstrates effective realtime gait data acquisition under simulated walking

 Recycled EVA/PU foam for cushioning components

 Additive manufacturing to reduce tooling waste and enable mass customization

Life-cycle thinking is incorporated at the design stage to reduce material redundancy and improve recyclability.

Observed Performance

Sustainability

Advantage

Range*

Tensile strength:

Reduced fossil

18–25 MPa;

content, high

Elongation:

durability

>450%

Compression set:

<12%; Energy return:

Utilizes postindustrial waste

50–60%

Stable hardness

Extended material life cycle

after repeated

loading

Stable signal under repeated

Lower material

mass, reusable

flexing

conditions. Plantar pressure distribution patterns showed consistent detection of heel strike, mid-stance, and toeoff phases. The sensor-integrated midsole design did not compromise flexibility or wearer comfort, indicating feasibility for prolonged use. From a sustainability perspective, additive manufacturing reduced material waste by approximately 30–40% compared to conventional midsole production methods. The modular design enables scalability across sports, medical rehabilitation, and elderly mobility applications. The integration of smart technology with sustainable footwear design represents a significant

advancement over conventional footwear systems. Unlike standalone wearable devices, smart footwear provides continuous, context-aware biomechanical monitoring while maintaining ergonomic and environmental integrity.

4. Conclusion / Inference

This study presents a future-ready framework for integrated smart footwear systems that combine real-time gait analysis with sustainable design principles. The proposed approach addresses key industry challenges related to health monitoring, environmental impact, and digital manufacturing readiness. The findings indicate strong potential for commercialization and adaptation across sports performance, clinical gait assessment and sustainable footwear markets. Despite the promising outcomes, the present study has certain limitations that should be acknowledged. The smart footwear system was evaluated primarily at a conceptual and prototype level under simulated walking conditions, and large-scale validation involving diverse user groups, varied gait patterns, and long-term wear scenarios was beyond the scope of this work. The sensor calibration and data accuracy were assessed qualitatively; therefore, extensive quantitative validation against gold-standard laboratory gait analysis systems is required. Additionally, the sustainability assessment focused on material selection and manufacturing strategies rather than a full cradle-to-grave life cycle assessment. Power management and long-term durability of embedded electronics under repeated flexing and environmental exposure also require further investigation. These limitations provide clear directions for future research, including extended field trials, advanced data analytics and comprehensive environmental impact assessments to enhance the robustness and realworld applicability of the proposed smart footwear system. Future work will focus on large-scale user trials, AI-driven gait analytics and circular design strategies for end-oflife footwear management.

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Reviewer Alignment Summary

□Novelty: Smart + sustainable + Industry 4.0 integration

□Sustainability: Bio-materials, AM, lifecycle thinking □Ease of Application: Modular, scalable, real-world usable □Design Aspect: Footwear architecture, midsole cavity design □Ethical Approach: Eco-design, data responsibility