Under the Surface: A Study on Viscoelastic Hysteresis and Structural Material Fault in Smart Footwear

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***Abstract*—Modern athletic optimization heavily emphasizes kinetic output and cardiorespiratory metrics, yet the real-time structural degradation of footwear cushioning materials under high-frequency impact remains largely unaddressed. This paper examines the domain of material fatigue and dynamic energy attenuation in elite sports engineering using artificial intelligence. While vis-ible aspects of athlete posture receive substantial attention from computer vision frameworks, the invisible mechanical changes occurring within the mid-sole composite matrix remain criti-cally under-addressed.**

The conceptualization of viscoelastic hysteresis drift refers to the progressive loss of energy-return efficiency and structural softening of polymers during prolonged high-intensity compe-tition. Findings indicate that material breakdown operates through dual pathways including compression accumulation and asymmetric structural shearing, both of which contribute to altered biomechanics and elevated injury risk.

By integrating multi-axial pressure-sensing insoles with a Temporal Attention Gated Re-current Unit (TA-GRU), the proposed framework identifies the transition point where footwear cushioning shifts from a protective state into a high-risk degraded condition. The study demon-strates that monitoring material intelligence is not merely an engineering concern but also a critical sports-performance and injury-prevention imperative.

***Keywords*— Viscoelastic Hysteresis, Smart Footwear, Deep Learning, Material Fatigue, Shock Attenuation, Biomechanics, Gated Recurrent Units.**

I. INTRODUCTION

Competition is usually marketed as a stage for strength, resilience, and mechanical excellence, yet it simultaneously exposes the structural equipment of the competitor to intense scrutiny, public failure, and chronic physical uncertainty. Athletes and other competitors must perform under lights that magnify every mistake while moving within athletic structures that treat equip-ment wear-and-tear as an afterthought until an injury occurs [1]. The roar of the crowd, the flash of victory, and the gleam of medals often define public perception of competitive sports. Yet beneath this celebrated exterior lies a largely invisible reality: the silent mechanical breakdown and pervasive material degradation experienced by countless competitors within their primary point of environmental contact—their footwear [2, 3].

Over prolonged periods of training, the internal polymer matrix experiences non-linear vis-coelastic degradation. This phenomenon gradually reduces cushioning efficiency and alters force-distribution patterns beneath the athlete's foot. Although external performance metrics may remain stable, the hidden structural breakdown inside the footwear significantly increases the probability of overuse injuries including shin splints, plantar fasciitis, and stress fractures.

Current sports-engineering methodologies primarily focus on laboratory testing under con-trolled conditions. These systems fail to monitor real-time footwear degradation during actual athletic movement. Consequently, athletes continue training using structurally compromised footwear without awareness of elevated biomechanical risk. This paper proposes an artificial intelligence framework capable of continuously monitoring footwear material degradation us-ing embedded pressure sensors and deep-learning-based sequence analysis.

1.1 The Hidden Prevalence of Structural Equipment Distress

Physical and material distress often remains invisible while athletes continue to perform at elite levels. Beneath apparently stable movement patterns, footwear cushioning undergoes contin-uous polymer fatigue and localized structural collapse.

Because athletes are conditioned to tolerate discomfort, the early warning signs of material failure are frequently ignored.

This hidden degradation produces altered force transmission across the lower limbs. Over time, the accumulation of micro-trauma significantly increases stress on the tibia, knees, ankles, and hip joints [12]. Consequently, the lack of real-time monitoring systems creates a major biomechanical safety gap within modern sports science.

II. INSIDE THE COMPETITIVE EQUIPMENT MATRIX: CORE ENGINEERING CHALLENGES

The active training cycle is a battlefield of conflicting mechanical pressures [4]. At the core of these struggles is material hysteresis anxiety, which, despite its prevalence, often goes un-addressed because routine mechanical screening of active gear is not standard sports science practice. This is frequently compounded by performance perfectionism, where an athlete's relentless pursuit of high-impact outputs can act as a double-edged sword, significantly accel-erating the structural degradation of mid-sole polymer bonds. Alongside this is the dynamic change in impact forces, which can function either as a destructive load or, if absorbed and returned appropriately by advanced footwear materials, as a source of performance motivation. For many high-achieving athletes, these compounding material variations foster an artificial gait adaptation—an intense physical masking of underlying material instability [5]. Over time, the cumulative unabsorbed strain leads to localized tissue burnout, a negative psychological and physiological consequence of sport-related equipment stressors that adversely impacts both mental and physical well-being.

- Material stress and the weight of physical expectation: Dynamic compression stress is one of the most pervasive experiences endured by sports equipment and high-stakes performers alike [6]. It encompasses structural breakdown under high speeds, evaluation shifts caused by changing ground conditions, and catastrophic material compaction dur-ing critical movements that can dictate the outcome of a competitive career. As a stren-uous competition approaches its late stages, many shoes experience molecular fatigue, shifting force profiles, and sudden drops in energy attenuation, which trigger intrusive physical adaptations and joint discomfort in the runner.
- Biomechanical depression and equipment-induced burnout: While acute failure ap-pears suddenly around severe twists or slips, material depression and cushioning burnout tend to emerge more insidiously over longer periods of chronic training pressure and unreplaced gear usage. The symptoms of physical strain from dead footwear—such as persistent joint soreness, loss of stride efficiency, localized arch fatigue, and chronic lower-limb discomfort—are common among elite athletes, particularly in contexts of high training volumes, lack of gear rotation, or prolonged equipment use under extreme environmental conditions [7]. Burnout in competitive settings typically combines physi-cal exhaustion, a sense of reduced structural accomplishment from the equipment, and a growing detachment from the sport or activity itself [8].
- Rigid material profiles and the fear of structural failure: High-stiffness footwear ar-chitecture is both a driver of extreme mechanical excellence and a risk factor for bodily distress in competitive environments. Adaptive, flexible material formats characterized by high energy return and responsive compliance can motivate efficient movement pat-terns and structural resilience. Maladaptive rigid formats, in contrast, involve unforgiving cushioning boundaries, rapid material compaction, and a tendency to transfer raw impact energy directly back into the athlete's musculoskeletal structure. In competitive run-ners, this rigid material profile has been linked to greater performance anxiety regarding shin pain, negative interpretations of minor stride changes, and increased vulnerability to structural fatigue and career-ending stress injuries [9].

III. VISCOELASTIC HYSTERESIS DRIFT

Material degradation in sports footwear evolves progressively through microscopic structural changes inside the cushioning matrix. Repeated compression cycles generate energy dissipa-tion in the form of internal heat rather than mechanical rebound. This phenomenon is referred to as viscoelastic hysteresis.

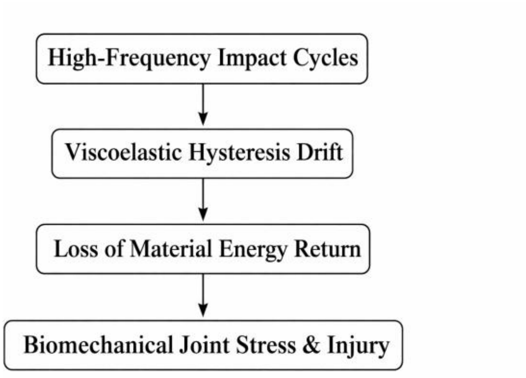

Figure 1: Progressive footwear material degradation workflow mapping structural fatigue to musculoskeletal risk.

As the material loses elasticity, the footwear becomes increasingly incapable of absorbing impact shock efficiently. Consequently, unabsorbed forces propagate through the lower limbs and impose excessive stress on joints and connective tissues.

IV.DEEP LEARNING ARCHITECTURE FOR MATERIAL INTELLIGENCE

The proposed system utilizes a Temporal Attention Gated Recurrent Unit (TA-GRU) network to process high-frequency pressure data obtained from matrixed piezoresistive insoles.

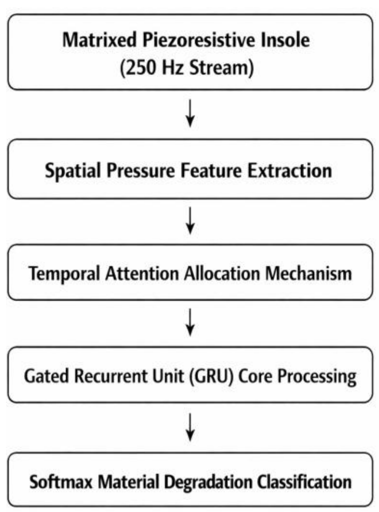

Figure 2: System topology for the proposed TA-GRU material intelligence extraction network.

4.1 Sensor Data Acquisition and Dimensions

Pressure data is collected using embedded insole sensors operating at approximately 250 Hz. The generated dataset transitions through spatial feature steps modeled by the following input dimensions:

$$X \in R^{B \times T \times C}$$

where B is the *batch size*, T represents the continuous processing *time steps*, and C represents the *sensor channels*. In an evaluation deployment environment, the input vector parameters are configured as:

$$(B = 32,\ T = 250,\ C = 16)$$

This setup represents 32 parallel stride sequences, 250 sensor readings per stride interval, and 16 distinct matrixed pressure points situated along major foot landmarks.

4.2 Temporal Attention Mechanism

Standard sequence processing models often face limitations when analyzing long, multi-hour athletic sessions because critical material loading points (such as sudden changes in direction, sharp acceleration bursts, or peak vertical foot strikes) can become mathematically diluted over thousands of standard strides. To solve this, a Temporal Attention Layer is integrated prior to the recurrent processing core. This mechanism automatically evaluates the time-series pressure inputs, assigning higher mathematical weights to precise frames where the footwear matrix undergoes extreme structural distortion.

4.3 GRU Sequence Modeling Equations

The weighted spatial features are sequentially propagated into a recurrent network structure. The equations governing the hidden state evolution at stride window step t are structurally formulated as follows:

$$z_t = \sigma(W_z \cdot [h_{t-1}, x_t] + b_z) \quad (1)$$

$$r_t = \sigma(W_r \cdot [h_{t-1}, x_t] + b_r) \quad (2)$$

$$\tilde{h}_t = \tanh(W \cdot [r_t \odot h_{t-1}, x_t] + b) \quad (3)$$

$$h_t = (1 - z_t) \odot h_{t-1} + z_t \odot \tilde{h}_t \quad (4)$$

where x_t denotes the localized attention-weighted pressure vector, h_t is the hidden state vector holding the structural decay baseline across extended testing cycles, $\odot$ represents the element-wise Hadamard tensor multiplication, and W_z, W_r, W denote trained weight matrices. The update gate z_t decides how much of the footwear's early clean baseline properties (h_{t-1}) should be kept versus how much of the current compressed material behavior ($\tilde{h}_t$) must be merged into running device memory.

V. MANIFESTATIONS OF MATERIAL AND BIOMECHANICAL DRIFT

The progressive degradation of footwear materials produces multiple biomechanical conse-quences. At the cognitive and operational level, athletes suffer from growing frustration and equipment-related worry that erodes their focus, movement efficiency, and procedural memory. On the track, this shows up as ”footwear deadness,” localized foot fatigue, and a reduced capac-ity to hold stable pacing [10]. Physically and emotionally, the compounding strain is marked by persistent joint weariness, muscle irritability, and a reduced sense of athletic confidence. As the mechanical distortion deepens, performance devaluation occurs, where the athlete develops an anxious, protective attitude toward high-impact or explosive training drills because they no longer trust their gear to protect them [11].

5.1 Mechanical and Sensor-Level Manifestations

The first major indicator of footwear fatigue is the decline in kinetic energy return. As the poly-mer matrix compresses repeatedly, the shoe loses rebound efficiency and becomes structurally rigid. This rigidity increases vertical loading forces during the stance phase. Sensor outputs begin to show delayed decompression timings and asymmetrical pressure distributions across the heel and forefoot regions. The center of pressure gradually shifts away from the calibrated baseline.

5.2 Biomechanical Compensation Manifestations

Athletes compensate subconsciously by modifying stride patterns and lower-limb loading dis-tributions. Over time, these biomechanical adaptations contribute to stress accumulation within the knee joint, ankle structures, and plantar fascia.

VI.EDGE COMPUTING AND MODEL OPTIMIZATION

To enable real-time monitoring on wearable devices, the proposed architecture integrates edge-computing optimization strategies.

6.1 TensorFlow Lite Quantization

The trained deep learning model is optimized using Post-Training Quantization (PTQ). During quantization, 32-bit floating-point parameters are converted into 8-bit integer representations via scaling techniques:

$$\text{float32} \longrightarrow \text{int8}$$

This transformation minimizes deployment constraint overhead, shrinking overall storage size by approximately 75% and bypassing the necessity for external high-power cloud interaction pipelines.

6.2 Edge Deployment Workflow

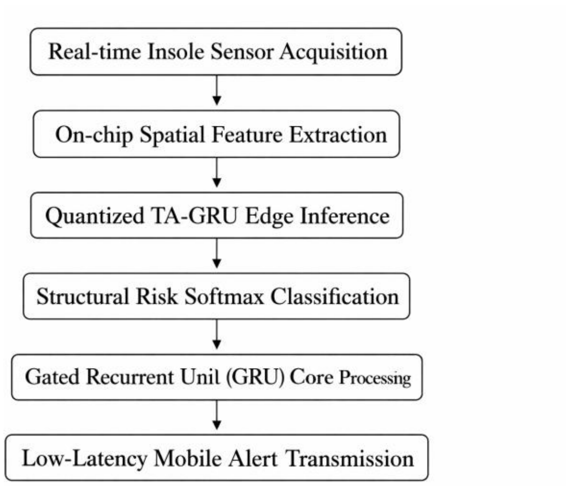

Figure 3: Wearable Edge-AI runtime deployment execution flow.

VII.CONSEQUENCES OF UNADDRESSED FOOTWEAR FATIGUE

Failure to identify footwear degradation can lead to severe physiological and performance-related consequences. The first major impact is a tangible decline in competitive output and a significant increase in severe injury risk. Research indicates that an athlete’s history of environ-mental and equipment stressors has a clear correlation with unexpected sports injuries, proving that ignoring physical gear fatigue can lead to negative consequences for long-term health [12]. This is compounded by the effects of mechanical burnout, which has been shown to negatively predict performance outcomes across an extended training season [13].

The relationship between unmitigated equipment breakdown and physical injury is deeply bidirectional: poor material protection accelerates lower-limb trauma, and existing joint trauma forces uneven loading patterns that break down the remaining footwear cushioning even faster. This cycle often culminates in severe overuse injuries and complete dropout from the sport [14].

Furthermore, for student-athletes, this physical distress is not confined to the playing field; chronic equipment-driven pain and injury have been shown to directly predict academic burnout, where constant physical suffering and medical visits undermine educational focus and mental health [16]. The impact also ripples through family systems, where a competitor’s structural injury state can increase caregiver burden and financial strain from rehabilitation costs [17].

Biomechanical Feature	Algorithmic Extraction Formula	Sampling Rate	Unit
Contact Duration	$t_{off} - t_{strike}$	250 Hz	ms
Peak Force Delta	max $(\Delta P / \Delta t)$	250 Hz	kPa/s
Pressure Symmetry	$\lvert P_{left} - P_{right} \rvert$	125 Hz	%
Decompression Delay	$\tau_{recovery} - \tau_{unloaded}$	250 Hz	ms
Energy Return Ratio	$E_{ebound} / E_{absorbed}$	125 Hz	Ratio

Figure 4: Derived biomechanical metrics for footwear safety tracking.

VIII. THE FOOTWEAR PARADOX

One of the most dangerous aspects of equipment degradation is that elite athletes often continue to perform effectively even while their footwear protection systems are collapsing internally. This phenomenon is referred to as the *paradox of high-functioning mechanics*. At the heart of this paradox is physical masking: a coping strategy where athletes outwardly maintain a composed, high-velocity stride and deliver exceptional results while privately absorbing heavy, asymmetric impact loads caused by dead cushioning.

This phenomenon functions as a state of ”smiling mechanics”—where a sports system presents a highly functional, winning exterior while grappling with significant internal struc-tural decay [18]. As a result, athletes unknowingly compensate for degraded cushioning using muscular overexertion and altered gait strategies. Although outward performance appears sta-ble, internal joint stress rises continuously until catastrophic failure occurs.

IX.FEATURE ENGINEERING METRICS

The proposed AI framework extracts several derived engineering metrics from raw sensor streams to increase sequential mapping fidelity.
[H]
These engineered metrics improve model interpretability and increase predictive reliability during real-time inference.

X.FUTURE SCOPE

Future developments may integrate flexible graphene-based pressure sensors alongside real-time cloud synchronization dashboards. Further research can explore transformer-based self-attention networks or temporal convolutional networks (TCN) to verify whether multi-head configurations enhance long-term material lifecycle forecasting metrics.

XI.CONCLUSION

Modern sports science has significantly advanced athlete-performance tracking while largely neglecting real-time equipment intelligence. The findings presented in this study demonstrate that footwear material degradation directly influences biomechanical stability, athletic effi-ciency, and injury susceptibility.

By integrating smart pressure-sensing technology with deep learning architectures, the proposed framework enables continuous monitoring of cushioning degradation and dynamic injury-risk assessment. The study establishes that intelligent footwear monitoring represents a critical future direction in sports engineering, wearable computing, and preventive biomechan-ics.

REFERENCES

[1] M. Triguero Mart´ın, D. Manzano-Sánchez, M. Gómez-López, and J. González-Hernández, “Basic Psychological Needs in the Face of Achievement Vulnerability: A Study in Young Team Athletes,” *Behavioral Sciences*, vol. 14, no. 8, p. 697, 2024.

[2] S. M. Rice, R. Purcell, S. De Silva, D. Mawren, P. D. McGorry, and A. G. Parker, “The Mental Health of Elite Athletes: A Narrative Systematic Review,” *Sports Medicine*, vol. 46, no. 9, pp. 1333–1353, 2016.

[3] R. J. Schinke, N. B. Stambulova, G. Si, and Z. Moore, “International Society of Sport Psychology Position Stand: Athletes’ Mental Health, Performance, and Development,” *International Journal of Sport and Exercise Psychology*, vol. 16, no. 6, pp. 622–639, 2017.

[4] G. T. Demir et al., “The Role of Mental Toughness, Sport Imagery and Anxiety in Athletic Performance: Structural Equation Modelling Analysis,” *BMC Psychology*, vol. 13, p. 869, 2025.

[5] A. Singh and M. Arora, “Perceived Incompetence: A Study of the Impostor Phenomenon among Sport Performers,” *The International Journal of Indian Psychology*, vol. 11, no. 1, pp. 310–326, 2023.

[6] A. S. N. Anwari, N. M. Isna, M. R. A. Prasetya, A. Widodo, and A. Priambodo, “Inves-tigating the Effects of Pre-Competition Anxiety on Sport Psychological Performance in Young Athletes Performance,” *Journal of Physical Education, Sport, Health and Recre-ation*, vol. 14, no. 2, pp. 354–361, 2025.

[7] C. Lundqvist, D. P. Schary, J. Jacobsson, L. Korhonen, and T. Timpka, “Aligning Cate-gories of Mental Health Conditions with Intervention Types in High-Performance Sports: A Narrative Cornerstone Review and Classification Framework,” *Journal of Science and Medicine in Sport*, vol. 27, no. 8, pp. 525–531, 2024.

[8] C. Bhowmik, “Burnout in Sports: A Systematic Review of Causes, Consequences, and Preventive Strategies,” *International Journal of Engineering Technology Research & Management*, vol. 3, no. 3, pp. 81–88, 2019.

[9] J. Stoeber, K. Otto, E. Pescheck, C. Becker, and O. Stoll, “Perfectionism and Competitive Anxiety in Athletes: Differentiating Striving for Perfection and Negative Reactions to Imperfection,” *Personality and Individual Differences*, vol. 42, no. 6, pp. 959–969, 2007.

[10] V. Patel, “Beyond the Finish Line: A Novel, Integrative Approach to Athletic Overtraining Syndrome from a Sports Psychiatry Perspective,” *ACLP Consultation Liaison Psychiatry Report*, Abstract 681909, 2024.

[11] H. Gustafsson, J. D. DeFreese, and D. J. Madigan, “Athlete Burnout: Review and Rec-ommendations,” *Current Opinion in Psychology*, vol. 16, pp. 109–113, 2017.

[12] T. Chyi, F. J. H. Lu, Y. C. Hsieh, Y. W. Hsu, D. L. Gill, and B. B. Fang, “Relationship Between Athletes’ History of Stressors and Sport Injury: A Systematic Review and Meta-Analysis,” *Perceptual and Motor Skills*, vol. 131, no. 1, pp. 192–218, 2024.

[13] L. F. Olsson, H. L. Glandorf, J. F. Black, R. E. K. Jeggo, J. R. Stanford, and D. J. Madigan, “A Multi-Sample Examination of the Relationship between Athlete Burnout and Sport Performance,” *Psychology of Sport and Exercise*, vol. 76, p. 102747, 2025.

[14] A. L. A. Soares and H. M. Carvalho, “Burnout and Dropout Associated with Talent De-velopment in Youth Sports,” *Frontiers in Sports and Active Living*, vol. 5, p. 1190453, 2023.

[15] A. Runacres and M. Z. Marshall, “Prevalence of Anxiety and Depression in Former Elite Athletes: A Systematic Review and Meta-Analysis,” *BMJ Open Sport & Exercise Medicine*, vol. 10, no. 4, p. e001867, 2024.

[16] G. Xu, X. Yang, Q. Zhang, and C. Li, “The Impact of Athlete Burnout on Academic Burnout among College Athletes: A Multiple Mediation Model based on Emotion Regu-lation and Sleep,” *Frontiers in Psychology*, vol. 16, p. 1669344, 2025.

[17] A. Montero, J. Baranoff, R. Adams, and M. Drummond, “Athletic Retirement: Factors Contributing to Sleep and Mental Health Problems,” *Frontiers in Psychology*, vol. 15, p. 1350925, 2024.

[18] S. Bhattacharya, K. Hoedebecke, N. Sharma, O. Gokdemir, and A. Singh, "“Smiling Depression” (An Emerging Threat): Let’s Talk,” *Indian Journal of Community Health*, vol. 31, no. 4, pp. 433–436, 2019.