CORPUS PUBLISHERS

Journal of Mineral and Material Science (JMMS)

ISSN: 2833-3616

Volume 7 Issue 2, 2026

Article Information

Received date : June 3, 2026

Published date: July 7, 2026

***Corresponding author**

Nidal H Abu-Hamdeh, Department of Mechanical Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

DOI: 10.54026/JMMS/1138

Keywords

Coefficient of Restitution; Kinetic Friction Coefficient; Sports Tribology; Mechanical Interlocking; Polymer Matrix Composites

Research Article

A Tribological Aad Mechanical Analysis of Boot-Ball Interfaces in Association Football: Rebound Dynamics and Friction Coefficients Under Varying Environmental Constraints

Alsuwat AA, Khoshaim An and Abu-Hamdeh NH*

Department of Mechanical Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia

Abstract

This study characterizes the dynamic Coefficient f Restitution (e) and the Kinetic Friction Coefficient (μ) across three distinct footwear upper materials-textured (PMC-T), hybrid (PMC-H), and smooth (PMC-S)-interfacing with three match ball casings exhibiting variable topography and damping characteristics (BC-G, BC-D, and BC-E). The results indicate that impact dynamics are predominantly influenced by the ball casing formulation; specifically, the low-hysteresis BC-E casing paired with the PMC-S upper yielded the highest global restitution (e = 0.805). Conversely, tribological performance was found to be governed primarily by surface topography and environmental moisture. The macro-textured PMC-T coupled with the micro-grooved BC-G casing demonstrated optimal frictional performance ($\mu_{dry,peak} \approx 0.66$; $\mu_{dry,mean} = 0.61$), a phenomenon attributed to enhanced mechanical interlocking mechanisms. The introduction of an aqueous medium facilitated micro-hydroplaning, resulting in a systematic degradation of performance across all interfaces, with relative friction reductions ranging from 27.6% to 33.3%. Ultimately, these mechanical metrics were contextualized within a tactical performance framework, suggesting that while smooth, low-damping pairings maximize normal kinetic energy transmission for long-range striking, high-friction, textured interfaces optimize tangential force transmission, thereby enhancing control and spin generation in wet-weather conditions.

Introduction

The tribological interaction between a football boot's upper material and the ball's surface plays a vital role in determining ball behavior, spin rate, and launch velocity during passing and shooting [1,2]. Modern football footwear relies extensively on engineered polymers and surface textures designed to optimize the dynamic coefficient of friction [3]. Early studies characterized these materials as isotropic elastomeric surfaces, assuming friction to be constant [4]. However, contemporary sports engineering has established that the boot-to-ball interaction involves a highly nonlinear viscoelastic response, governed by both adhesion and mechanical hysteresis [5]. The frictional properties of the shoe upper directly dictate the efficiency of energy transfer and tactile control, balancing the trade-off between energy conservation and directional accuracy via spin generation [6]. A critical challenge in sports tribology is the dramatic variance in frictional performance caused by ambient moisture [6]. Under dry conditions, contact mechanics are dominated by interfacial adhesion at the microscopic asperities of the polymer surfaces [7]. When water is introduced, it acts as a lubricant, forming a boundary-layer film that reduces adhesion [8]. At the onset of high-speed impact (0-5 ms), a phenomenon known as micro-aquaplaning occurs, in which the fluid film cannot escape rapidly enough, creating a hydrodynamic lubrication regime that drastically reduces friction [9]. To mitigate this, advanced outsoles and uppers employ micro-grooves or hydrophobic texturing designed to channel fluid away from the contact zone, encouraging a transition to boundary or mixed lubrication by 15 ms where rubber-like asperities can establish mechanical interlocking [10]. Consequently, evaluating the transient friction profile under alternating environmental matrices is essential to mapping real-world game performance [11]. According to classical friction theories, the coefficient of friction is independent of the normal load. However, elastomeric polymers deviate significantly from Amontons' laws due to structural compliance [12]. As the normal force (Fn) escalates-such as during structural loading or when a player adds downward compression-the actual area of contact expands non-linearly [13]. Initially, an increase in normal load promotes deeper mechanical penetration of texturized features (such as rubber dimples or sticky knit textures) into the football's outer casing, thereby increasing μ [14]. Yet, beyond a critical threshold, the asperities become fully flattened or saturated, leading to a localized drop in the apparent coefficient of friction as the adhesion-to-load ratio stabilizes [15]. Tracking this transient contact phenomenon millisecond by millisecond provides fundamental insight into the loading phase (compression), peak engagement (maximum contact area), and the subsequent unloading phase as the ball departs the upper [16,17].

Experimental Procedure

To minimize variability due to wear, competition-grade football match balls and matching elite boots were sourced from three different material formulations (BC-G, BC-D, BC-E; PMC-T, PMC-H, PMC-S, respectively, as illustrated in (Table 1). Boot upper materials (texturized synthetic, Flyknit/TPU hybrid, or thin composite laminates) were cut to size and bonded (cyanoacrylate) to a rigid aluminum substrate to ensure a planar contact geometry, while match balls were either left intact and pressurized to 0.80±0.02bar under controlled laboratory conditions (20±1 °C and 53±4% Relative Humidity (RH)) for rebound testing, or sectioned and flattened analogously for subsequent tribological testing. The normal Coefficient of Restitution (e) was measured using a vertically oriented drop-mass impact rig. An inflated ball was held in a rigid steel fixture, and a 5.0 kg carriage containing the boot specimen was dropped from a nominal height of 1.00 m by an electromagnetic latch. Velocities before and after impact (v_i, v_f) and the associated drop/rebound heights (h_i, h_r) were measured synchronously via a high-speed imaging system (5000 fps) and a linear optical encoder, enabling the calculation of e through the kinematic equivalence:

$$e = \frac{v_f}{v_i} = \sqrt{h_r / h_i} \quad (1)$$

To ensure statistical reliability, more than 10 repetitions per ball-boot combination were performed, with a 120 s interval maintained between repetitions to minimize the effects of viscoelastic pre-conditioning. The kinetic friction coefficients (μ) were measured using a computer-controlled linear tribometer designed to simulate ball-on-flat sliding interactions. Flattened ball-casing specimens were attached to a horizontal translation stage, and the boot-mounted plate was engaged using a vertically actuated loading arm equipped with a dual-axis piezoelectric load cell with a resolution of ±0.01N. To evaluate the steady-state dynamic friction behavior over an extended contact timeline, the linear tribometer was operated in a reciprocating mode with a stroke length of 100 mm at a constant sliding velocity of 0.1 m/s. Each test run lasted 25 seconds (equivalent to 12.5 full cycles). The reported continuous friction coefficient (μ) profile is a filtered moving average of the absolute friction force across multiple cycles, eliminating directional switching artifacts. The (μ) value was computed by sampling tangential friction forces (F_f) at 1000 Hz under dry conditions at a constant normal load (F_n) of 50 N, using the following equation:

$$\mu = F_f / F_n \quad (2)$$

Table 1: Materials and structural classification of the testing interfaces.

Interface Component	Academic Code	Base Material Composition	Topographical & Structural Characteristics
Boot 1	PMC-T (Polymer Matrix Composite - Textured)	Thermoset Polyurethane (PU) with elastic TPU overlays.	Engineered macro-textural features and micro-drainage channels.
Boot 2	PMC-H (Polymer Matrix Composite - Hybrid)	Multi-layered Knitted Polyester (Flyknit)/TPU hybrid laminate.	Viscoelastic composite architecture with shallow micro-grooves.
Boot 3	PMC-S (Polymer Matrix Composite - Smooth)	Highly cross-linked thin polyurethane formulation.	Planar, smooth surface geometry relying on boundary adhesion.
Ball Casing 1	BC-G (Ball Casing - Grooved)	Thermally bonded Polyurethane (PU) outer shell with dense backing.	Outer micro-groove topography with intermediate elastomeric layers.
Ball Casing 2	BC-D (Ball Casing - Damping)	High-damping polymeric casing laminate with a butyl rubber bladder.	Shallow micro-textured surface with a high hysteretic loss profile.
Ball Casing 3	BC-E (Ball Casing - Elastic)	Low-hysteresis synthetic elastic core and polyurethane film.	Comparatively planar/smooth outer morphology with low internal damping.

Results and Discussions

Rebound performance characteristics

The Coefficient of Restitution (*e*) was quantified for all ball-boot permutations to evaluate energy restitution efficiency. (Table 2) presents the complete matrix of measured *e* values, organized by boot upper formulation (PMC-T, PMC-H, PMC-S) and ball casing variant (BC-G, BC-D, BC-E), as shown in (Figure 1).

Table 2: Measured coefficients of restitution (*e*) for all ball-boot combinations.

Boot Variant	BC-G	BC-D	BC-E	$\bar{e}_{boot}$
PMC-T	0.775	0.77	0.785	0.777 ± 0.008
PMC-H	0.762	0.758	0.772	0.764 ± 0.007
PMC-S	0.794	0.788	0.805	0.796 ± 0.009
$\bar{e}_{ball}$	0.777±0.016	0.772±0.015	0.787±0.017	Global $\bar{e}$ = 0.779 ± 0.013

There was a significant main effect of boot formulation (p<0.001) and ball casing (p=0.003) on restitution performance, with no significant interaction effect (p=0.12), as determined by a two-way ANOVA (α=0.05). For all ball substrates, the PMC-S boot configuration always had the highest e-values with a maximum of e=0.805 for the BC-E ball and a minimum of e=0.788 for the BC-D ball. On the other hand, the PMC-H boot dissipated the most energy, and the homogenous PMC-H/BC-D combination had the minimum global evalue (0.758). The ball casing BC-E exhibited the highest mean restitution ($\bar{e}$=0.787±0.017) independent of boot interface. In contrast, BC-D exhibited the highest energy absorption ($\bar{e}$=0.772±0.015). This demonstrates the dominant effect of ball casing formulation on global impact dynamics.

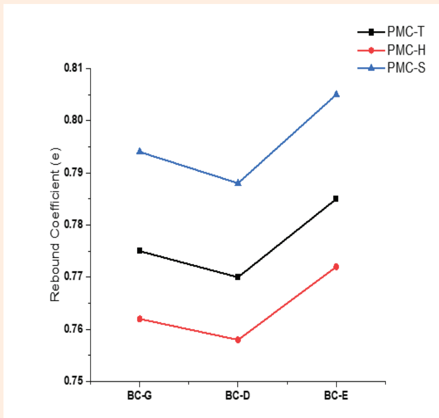

Figure 1: Rebound performance characteristics (coefficient of restitution, e) across various ball–boot interface configurations.

Tribological performance and friction analysis

Friction and Tribological Characterization. (Figure 2) presents the transient friction profiles of the three different material combinations during a continuous 25-second test. All investigated configurations show a structurally consistent, nonlinear parabolic friction trajectory with a fast initial run-in phase, a distinct peak of the coefficient of friction (μ) between 16 and 17 seconds, and a subsequent steady decrease. The PMC-T/BC-G coupling (Boot 1/Ball Casing 1) exhibited the best overall frictional response over the test period with a maximum coefficient of friction of approximately μ=0.66. The good frictional performance is primarily attributed to the synergistic effect of mechanical interlocking between the designed macro-textural features of the textured polymer matrix composite (PMC-T) and the micro-groove topography of the thermally bonded outer shell (BC-G). The hybrid system, PMC-H/BC-D (Boot 2/Ball Casing 2), on the other hand, exhibited an intermediate friction profile, with a peak at μ≈0.61. This behavior is a manifestation of a balance between the viscoelastic hysteretic losses inherent to the high-damping butyl rubber/laminate architecture and the reduced mechanical engagement of the shallow micro-grooves. The lowest frictional resistance was always observed for the combination PMC-S/BC-E (Boot 3/Ball Casing 3), with a maximum μ≈of 0.57. The lack of substantial macro- or micro-texturing on the smooth, planar polyurethane formulation (PMC-S) and the low-hysteresis elastic casing (BC-E) precludes mechanical interlocking, limiting the interface to boundary adhesion and resulting in a significantly lower overall friction coefficient.

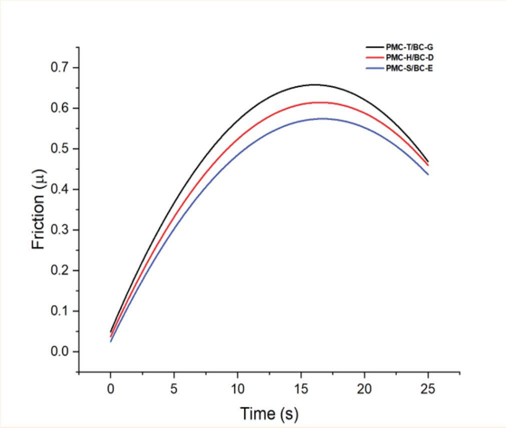

Figure 2: Transient friction profiles (coefficient of friction, μ) of the evaluated boot upper and ball casing interfaces over a continuous 25-second testing timeline.

Interfacial friction behavior under dry and wet conditions

The kinetic friction coefficients (μ) for cross-material and homogenous pairings were measured under dry and wet conditions (Tables 3 & 4). All configurations experienced a systematic decrease in μ upon the introduction of an aqueous phase with absolute drops (Δ) of 0.16-0.18 and relative performance losses of 27.6-33.3%.

Table 3: Friction coefficients for cross-material interfaces.

Interface (Boot/Ball)	μ_{dry}	μ_{wet}	$\Delta\mu$	% Loss
PMC-T / BC-G	0.61	0.44	0.17	27.9
PMC-H / BC-D	0.58	0.42	0.16	27.6
PMC-S / BC-E	0.55	0.37	0.18	32.7

The tribological performance of the investigated Polymer Matrix Composites (PMCs) varied significantly depending on both the matrix formulation and the testing environment. Across all three composite series (PMC-T, PMC-H, and PMC-S), a consistent trend emerged: the coefficient of friction (μ) was significantly lower under wet conditions than under dry conditions, driven primarily by the lubricating effect of the fluid film. As illustrated in (Figure 3), the PMC-T series exhibited its highest frictional resistance during dry sliding across the various ball casing variations. For example, the PMC-T variant paired with casing 'G' reached a peak dry μ of approximately 0.61, which decreased to roughly 0.44 under wet sliding. A similar environmental dependency was observed in the PMC-H series (Figure 4). Here, the maximum dry μ reached approximately 0.58 (with casing variant 'E'), while the wet environment reduced this value to a steady 0.42. The PMC-S series (Figure 5) exhibited a slightly modified friction profile. It consistently recorded the lowest overall wet μ values in the study ($\approx 0.34 - 0.37$).

However, its dry friction profile peaked differently, reaching a maximum dry μ of 0.55 when paired with the 'D' casing configuration. A direct comparison across all three series and casing configurations is presented in (Figure 6). The data confirms that the PMC-T configuration generally produces the highest overall friction coefficients in both environments, whereas the PMC-S configuration effectively minimizes friction, particularly during wet sliding. Ultimately, these findings demonstrate that targeted matrix modifications and specific ball casing pairings can successfully modulate the material's shear resistance and the stability of the interfacial lubricating film.

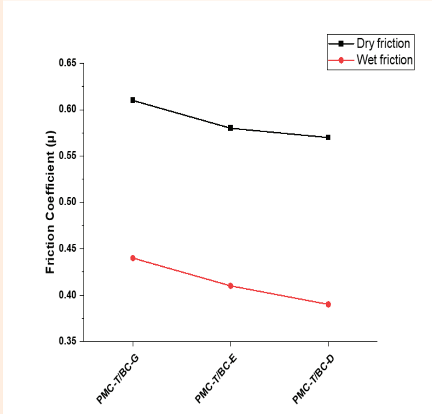

Figure 3: Comparison of dry and wet friction coefficients (μ) for various Polymer Matrix Composites (PMC-T) and different ball casing series variations.

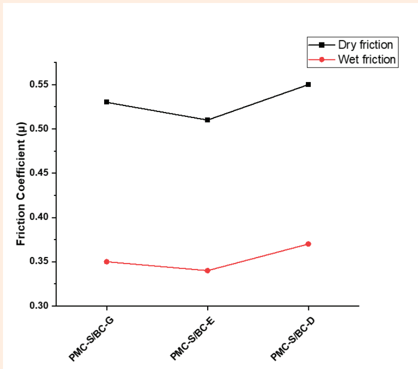

Figure 4: Comparison of dry and wet friction coefficients (μ) for the PMC-H polymer matrix composite paired with various ball casing series variants.

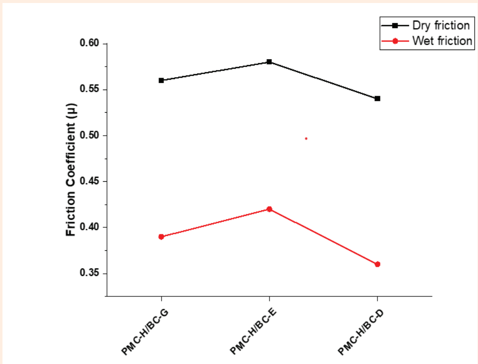

Figure 5: Comparative analysis of dry and wet friction coefficients (μ) for the PMC-S polymer matrix composite series across different ball casing configurations.

Citation: Alsuwat AA, Khoshaim A and Abu-Hamdeh NH (2026) A Tribological Aad Mechanical Analysis of Boot-Ball Interfaces in Association Football: Rebound Dynamics and Friction Coefficients Under Varying Environmental Constraints. J Miner Sci Materials. 7: 1138

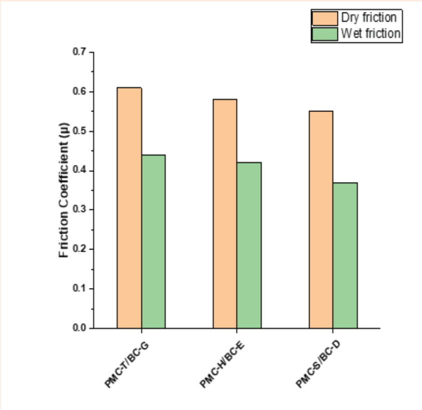

Figure 6: Comparative analysis of dry and wet friction coefficients (μ) across the three investigated Polymer Matrix Composite (PMC) series and their corresponding ball casing configurations.

Performance implications and tactical translation

The measured differences in e and μ are directly translated into measurable differences in ball-handling dynamics on the pitch (Table 4). The best combination for long-range striking is the PMC-S/BC-E, with the greatest energy return (e=0.805), but it also requires the greatest technical precision to receive the ball softly due to its smaller Δt. The PMC-T/BC-G configuration, with the highest friction coefficients (μ_"dry"=0.61, μ_"wet"=0.44), optimizes tangential force transmission for spin-heavy techniques while retaining wet-weather grip through effective drainage. The PMC-H/BC-D system, on the other hand, focuses on energy absorption (e=0.758) to allow for close-control dribbling at the expense of peak launch velocity.

Table 4: Mechanical performance metrics and tactical applicability of homogenous pairings.

Pairing	Dominant Attribute	Optimal Application	Kinematic Trade-off
PMC-S / BC-E	Ultra-high *e*(0.805); minimal hysteresis	Long-range striking; explosive clearances	Reduced Δt; diminished cushioning tolerance
PMC-T / BC-G	Elevated μ (0.61 dry; 0.44 wet); drainage	High-spin trajectories; wet-weather control	Increased rotational resistance during rapid release
PMC-H / BC-D	Enhanced damping ($e = 0.758$); controlled deformation	Close-quarters dribbling; high-frequency short passing	Lower exit velocity; greater muscular demand for distal passes

Conclusion

This study presents a comprehensive tribological and mechanical characterization of the boot-ball interface in association football, establishing that the interfacial mechanical response is highly sensitive to material formulation, surface topography, and environmental constraints. The investigation demonstrates that impact and friction dynamics operate through distinct mechanical pathways: normal energy restitution (e) is predominantly governed by the viscoelastic and damping properties of the ball casing, whereas tangential friction coefficients (μ) are significantly influenced by the structural configuration and micro-textural drainage characteristics of the boot upper. The experimental data provide several fundamental implications for sports engineering and equipment design. Regarding topographical synergy, mechanical interlocking between macro-textured uppers (PMC-T) and micro-grooved casings (BC-G) produces optimal frictional performance ($\mu \approx 0.66$), which is critical for facilitating high-spin ball trajectories. In terms of environmental susceptibility, the presence of ambient moisture establishes a boundary lubrication regime that compromises interfacial adhesion, resulting in an absolute reduction in friction $(\Delta\mu)$ of up to 0.18 and a relative performance decrement of up to 33.3% across smooth or high-damping material formulations. Finally, regarding tactical optimization, the measured mechanical profiles directly correlate with on-field performance, highlighting distinct functional trade-offs. Specifically, high-restitution pairings (PMC-S/BC-E, e=0.805) maximize kinetic energy transfer for high-velocity ball projection at the expense of tactile control, whereas high-damping pairings (PMC-H/BC-D) enhance proximal ball retention and close-quarters maneuverability.

References

1. Tan AM, Weizman Y, Alam F, Fuss FK (2020) The coefficient of friction of soccer balls. Proceedings 49(1): 92.
2. Ishii H, Sakurai Y, Maruyama T (2014) Effect of soccer shoe upper on ball behavior in curve kicks. Scientific Reports 14(4): 6067.
3. Demeco A, Marotta N, Megna M, Racinelli A, Pansera B, et al. (2026) Functional design and clinical implications of modern soccer footwear: A comprehensive narrative review. Journal of Functional Morphology and Kinesiology 11(1): 62.
4. Mathauer K, Embs F, Wegner G (1989) Structure, properties and applications of polymeric langmuir–blodgett films. In: Allen G, Bevington JC, (Eds.), Comprehensive polymer science and supplements. Pergamon: Amsterdam, pp. 449-470.
5. Payne T, Mitchell S, Bibb R, Waters M (2015) Evaluation of new multi-material human soft-tissue simulants for sports impact surrogates. Journal of the Mechanical Behavior of Biomedical Materials 41: 336-356.
6. Sterzing T, Hennig EM (2007) The influence of friction properties of shoe upper materials on kicking velocity in soccer. Journal of Biomechanics 40: S195.
7. Myshkin N, Kovalev A, Spaltman D, Woydt M (2014) Contact mechanics and tribology of polymer composites. Journal of Applied Polymer Science 131(3).
8. Fang Y, Ma L (2023) Mechanic model of water-based boundary lubricated contact based on surface force effects. Friction 11: 93-108.
9. He Z, Jamil MI, Li T, Zhang Q (2022) Enhanced surface icephobicity on an elastic substrate. Langmuir 38(1): 18-35.
10. Kindrachuk M, Radionenko O, Kryzhanovskyi A, Marchuk V (2014) The friction mechanism between surfaces with regular micro grooves under boundary lubrication. Aviation 18(2): 64-71.
11. Xie Z, Zhu W (2021) Theoretical and experimental exploration on the micro asperity contact load ratios and lubrication regimes transition for water-lubricated stern tube bearing. Tribology International 164: 107105.
12. Kalin M, Jan P (2025) Understanding the friction laws of Amontons and Coulomb by evaluating the real contact area. Friction 13(1): 9440986.
13. Ciavarella M (2025) On the dependence of static friction coefficient on normal load. Tribology Letters 73: 130.
14. Lyashenko IA, Popov VL, Borysiuk V (2023) Indentation and detachment in adhesive contacts between soft elastomer and rigid indenter at simultaneous motion in normal and tangential direction: Experiments and simulations. Biomimetics 8(6): 477.
15. Hong S, Asai T (2017) Aerodynamic effects of dimples on soccer ball surfaces. Heliyon 3: e00432.
16. Marengo M, Antonini C, Roisman IV, Tropea C (2011) Drop collisions with simple and complex surfaces. Current Opinion in Colloid & Interface Science 16: 292-302.
17. Scuderi MM, Carpenter BM, Marone C (2014) Physicochemical processes of frictional healing: Effects of water on stick-slip stress drop and friction of granular fault gouge. Journal of Geophysical Research: Solid Earth 119(5): 4090-4105.