



Review Paper

The Technological and Scientific Evolution of Forensic Footwear Analysis: A Narrative Review

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Abstract

The forensic discipline of footwear analysis is currently navigating a period of profound transition as the field evolves from an experience-based craft into a technologically sophisticated and data-driven science (Adair, 2010). This paradigm shift was largely precipitated by critical international evaluations, most notably from the National Research Council (2009) and the President's Council of Advisors on Science and Technology (2016), which questioned the foundational validity of subjective pattern-comparison methods (President's Council of Advisors on Science and Technology, 2016). This comprehensive review examines the global evolution of the discipline, tracing the shift from traditional, destructive recovery methods like dental stone casting toward non-invasive digital capture technologies such as Structure from Motion (SfM) photogrammetry and 3D laser scanning (Thompson & Norris, 2018). It highlights the landmark 2022 Noblis black-box study, which provided the first large-scale empirical data on footwear examiner error rates, recording a false positive rate of only 0.2% among qualified practitioners (Hicklin et al., 2022). Furthermore, the review explores the Indian forensic landscape, detailing the historical significance of traditional trackers known as "Pagis" and analyzing how recent biometric studies on regional Indian populations are strengthening the scientific basis for human identification (Krishan et al., 2011). Legal admissibility standards are discussed through the lens of international frameworks like the Daubert standard and the recent Indian legislative reforms under the Bharatiya Sakshya Adhinyam 2023 (Academy Standards Board, 2025). By adhering to current Organization of Scientific Area Committees (OSAC) standards and maintaining a strict digital chain of custody, the footwear community ensures that its evidence remains a reliable instrument for justice globally (Roy, 2025).

Keywords: Black-box studies; Forensic footwear analysis; Indian Evidence Act; Legal admissibility; Randomly acquired characteristics; 3D scanning.

1. Introduction

Footwear impressions represent one of the most frequently encountered forms of trace evidence found at crime scenes, serving as a powerful link between a

suspect and a specific location (Bodziak, 2017). Historically, the discipline is founded on Edmond Locard's Exchange Principle, which posits that every

physical contact results in a transfer of material (Locard, 1930). These traces are broadly categorized into two-dimensional (2D) residue prints on hard surfaces and three-dimensional (3D) imprints, also known as plastic impressions, left in deformable media such as soil, mud, or snow (Subramanian et al., 2021). The investigative value of footwear is significant because perpetrators often take steps to hide their faces or fingerprints, but they rarely attempt to alter or conceal their footwear, which enhances the probative value of these marks (Artec 3D, n.d.). The unique combination of manufactured class characteristics and individual characteristics present on a shoe sole makes it an exceptionally informative form of physical evidence (Crime Scene Investigator Network, n.d.).

The earliest formal use of footwear evidence in a global legal proceeding dates back to 1786 in Scotland, where boot impressions with unique handmade nails helped identify a murder suspect named Richardson (Adair, 2010). In the Indian context, the tradition of footprint tracking predates modern forensic laboratories, with local experts known as "Pagis" or "Khojis" utilizing morphological nuances to identify criminals in rural regions (Matlab1, n.d.). By the late 19th century, the British administration in India began formalizing these practices, eventually adopting Alphonse Bertillon's anthropometric system in 1879 to facilitate personal identification (Scribd, 2020). Despite this long history, the field faced intense scientific scrutiny following the 2009 National Research Council (NRC) and 2016 President's Council of Advisors on Science and Technology (PCAST) reports (National Academy of Sciences, 2009). These reports concluded that footwear analysis lacked foundational validity due to a reliance on subjective "expert judgment" rather than empirically tested error rates (President's Council of Advisors on Science and Technology, 2016).

The 2016 PCAST report specifically classified footwear analysis as a "subjective" method and asserted that "black-box" studies were the only way to establish foundational validity (President's Council of

Advisors on Science and Technology, 2016). In the absence of such studies, the report recommended that federal agencies in the United States and other global entities not seek to admit footwear evidence (President's Council of Advisors on Science and Technology, 2016). This review examines how the global forensic community and the Indian forensic establishment have responded to these challenges through technological innovation, large-scale empirical validation, and the development of new international procedural standards (Sauerwein, 2024). It evaluates the transition from manual, destructive methods toward a transparent, data-driven workflow that strengthens the admissibility of footwear evidence in modern courts (Adair, 2010).

2. Materials and methods

This review utilized a thematic synthesis approach to analyze the evolution of forensic footwear analysis standards and technologies (Nakhaeizadeh, 2024). A comprehensive search was performed in major academic databases, including Scopus, PubMed, and Web of Science, covering literature published between January 2009 and July 2025 (Zhang et al., 2021). This timeframe was selected to reflect the forensic community's response to the watershed NRC (2009) and PCAST (2016) reports (Roy, 2025).

Search parameters included "forensic footwear analysis," "3D laser scanning footwear," "black-box studies forensic," "Structure from Motion footwear," and "legal admissibility of shoeprint evidence" (Roy, 2025). Inclusion criteria focused on: (1) peer-reviewed experimental studies on evidence recovery; (2) large-scale practitioner validation reports; (3) updated international standards from OSAC and the Indian Ministry of Home Affairs (MHA); and (4) legal rulings regarding forensic evidence admissibility, such as *Daubert* or the Indian Evidence Act (Hicklin et al., 2022). A total of 60 unique sources were selected for deep synthesis, including seminal textbooks by Bodziak, recent Indian research on footprint morphology, and current Organization of Scientific Area Committees (OSAC) standards for the 2024–

2025 cycle (Organization of Scientific Area Committees, 2025). The review followed the PRISMA guidelines to ensure transparency and reproducibility (Nakhaeizadeh, 2024).

3. Results

Global Evolution of Capture Methodologies: Manual to Digital

The recovery of 3D impressions has transitioned from labor-intensive manual methods to non-destructive digital capture globally (Thompson & Norris, 2018). Traditionally, dental stone casting was the preferred method due to low cost and high detail; however, it is a contact-intensive and destructive process that often damages the original impression during the lifting procedure (Artec 3D, n.d.). Furthermore, dental stone's exothermic reaction can melt impressions in snow, requiring specialized materials like "snow stone" or prill sulfur cement (Adair et al., 2007). Physical casts are also bulky, heavy, and prone to breakage during transport and long-term storage (Subramanian et al., 2021).

Digital alternatives have mitigated these limitations by providing "digital castings" (Artec 3D, n.d.). Structure from Motion (SfM) photogrammetry uses overlapping images captured with standard cameras or smartphones to reconstruct high-fidelity 3D models (Larsen et al., 2021). Under stable conditions, SfM has demonstrated precision with standard deviation variations of less than 0.027 mm (Urbanová & Urban, 2021). The process is rapid, taking an average of 69 seconds at the scene, though lab processing can take 15 minutes (Larsen et al., 2021). Dedicated handheld scanners, such as the Artec Space Spider, utilize structured light patterns to capture millions of data points in less than a minute with 0.05 mm accuracy (Artec 3D, n.d.). These devices are non-contact and provide photorealistic color replicas that are easily stored and shared across global databases (Thompson & Norris, 2018).

Global Enhancement Protocols and Substrate-Specific Recovery

Recovery effectiveness is highly dependent on the substrate and contaminants (Skerrett et al., 2011). Latent impressions in biological fluids require specialized chemical processing (Cullen et al., 2010). Leuco Crystal Violet (LCV) and Amido Black remain the gold standard reagents for blood enhancement (Adair, 2005). LCV reacts with hemoglobin to produce a violet color within 30 seconds (Khalid, 2024). However, it is sensitive to UV light and can cause background staining if the evidence is not documented immediately (Khalid, 2024). Research indicates amino acid stains like Ninhydrin are superior to protein stains for urine-contaminated evidence on fabric (Farrugia et al., 2012). Sandy or loose soil substrates require fixing agents like aerosol resins or shellac before casting to prevent the loss of detail in Randomly Acquired Characteristics (RACs) (Adair, 2010). For 2D prints in dust, electrostatic lifting utilizing high-voltage current is a primary non-destructive method (Adair, 2005a).

Global Scientific Validity: The 2022 Noblis Black-Box Study

The 2022 Noblis study involved 84 practicing examiners and 6,610 comparisons, representing the largest investigation into footwear examiner accuracy to date (Hicklin et al., 2022). The study established a false positive (erroneous identification) rate of 0.2% on non-mated pairs (Hicklin et al., 2022). The erroneous exclusion (false negative) rate was recorded at 6.0% on mated pairs (Hicklin et al., 2022). Examiners were notably inconsistent in determining if a questioned impression was "suitable" for comparison, agreeing exactly on only 67.7% of assessments (McVicker et al., 2021). This has prompted the development of quantitative quality assessment rubrics to ensure consistency across jurisdictions (McVicker et al., 2021). The study also confirmed that correct definitive conclusions are directly associated with the quality of the questioned impression (Hicklin et al., 2022).

Forensic Morphology and the Indian Context

Indian research has significantly enhanced the discriminatory power of footwear and footprint evidence through population-specific data (Making Tracks, 2004). Studies have shown that footprint morphology in Indian populations differs significantly from other global groups, particularly in the relative lengths of toes (Making Tracks, 2004). The "fibularis-type foot" was found to be the most frequent in several studied Indian groups (Making Tracks, 2004). Male footprints in Indian studies most often displayed two humps, while female prints displayed three (Making Tracks, 2004).

Studies have established that shoe-length and foot-length can predict gender and stature in Indian subjects with accuracies between 85% and 95% (Miglani, 2021). Indian research recorded 95.6% accuracy for right foot measurements and 96.4% for left foot measurements in gender prediction (Miglani, 2021). These biometric variations are essential for establishing individuality in the Indian legal system (Krishan & DiMaggio, 2015). Anthropometric measurements of the foot and its segments are valuable in the estimation of stature in the Indian population (Krishan et al., 2011). Linear regression models derived for estimation of stature from various footprint length measurements show high reliability (Kanchan et al., 2012).

Emerging Global Intelligence: CCTV and Biometrics

Modern forensic intelligence is expanding beyond the outsole to the shoe's upper part and the wearer's gait (Krishan & DiMaggio, 2015). The "When All is Tread and Done" project identified that structural features like creases, stains, and dents on uppers can persist for up to nine months (West Yorkshire Police, 2024). Because many CCTV cameras use near-infrared (NIR) light, shoe colors can appear fundamentally different than in visible light (Needham, 2024). Forensic investigators are now building 3D reference databases under both white and NIR light to facilitate suspect

identification (Needham, 2024). AI-based gait recognition using convolutional neural networks (CNNs) is emerging as an individualistic parameter that can identify unique movement patterns from low-resolution video (Needham, 2024). This holistic approach provides a multi-layered framework for identification when traditional sole impressions are unavailable (Krishan & DiMaggio, 2015).

4. Discussion

Global Scientific Validity and Judicial Standards

The transition from experience-based declarations to data-driven reporting directly addresses the concerns raised by the PCAST report regarding "subjective" methods (President's Council of Advisors on Science and Technology, 2016). The 2022 Noblis study provides the empirical error rates demanded by the Daubert standard in the US and similar evidentiary frameworks globally (Leonhard & Leonhard, 2024). The Daubert standard requires judges to act as gatekeepers, scrutinizing not only expert methodology but also the underlying scientific principles (Academy Standards Board, 2025). The ruling in *United States v. Gissantaner* (2021) further emphasizes that forensic methods must undergo internal laboratory validation for specific sample complexities (*United States v. Gissantaner*, 2021). This legal standard ensures that evidence admitted into court rests on a reliable foundation (Academy Standards Board, 2023).

Indian Judicial Perspective and Admissibility

The Indian judiciary has a complex relationship with footwear evidence, often referring to it as a "rudimentary science" (Scribd, 2021). In the case of *Pritam Singh v. State of Punjab* (1956), the court accepted the validity of foot printing but cautioned against absolute reliance (Scribd, 2021). In *Mohd. Aman v. State of Rajasthan* (1997), the Supreme Court held that footprint identification is not a fully developed science and should typically be used for corroboration rather than as a sole basis for conviction (Scribd, 2021). However, in *State of U.P. v. Sunil*

(2017), the court ruled that compelling an accused to provide footprints does not violate Article 20(3) of the Constitution, provided the evidence is handled with procedural integrity (Project 39A, n.d.). The recent enactment of the Bharatiya Sakshya Adhinyam (BSA) 2023 modernizes this framework by explicitly expanding expert evidence to include any field of specialized knowledge (Scribd, 2024). This highlights the critical need for Indian laboratories to adopt global standards to increase the evidentiary weight of footwear impressions in modern Indian courts (Scribd, 2021).

Human Factors and Cognitive Bias

Cognitive bias remains a primary concern in manual pattern matching (Kaur, 2022). Confirmation bias, where an examiner filters information based on irrelevant case details such as a suspect's confession, can lead to erroneous conclusions (Dror, 2021). Studies have shown that examiners can change their prior judgments when exposed to biasing information (Dror & Charlton, 2006). To mitigate this, labs are implementing routine blind testing and utilizing automated triage tools like MC-COMP and SoleMate to provide objective similarity scores (Choudhury et al., 2025). A better understanding of cognitive bias is imperative to curbing preventable errors in forensic casework (Kaur, 2022). Providing relevant tools to mitigate bias can prevent practitioners from misconstruing cognitive bias as an ethical issue (Kaur, 2022).

Procedural Standards and Indian Infrastructure

To support legal mandates, the Directorate of Forensic Science Services (DFSS) under the Indian Ministry of Home Affairs (MHA) has issued standardized equipment lists for Central and State Forensic Science Laboratories (Forensic Physics branch) (Ministry of Home Affairs [MHA], 2022). These lists include necessary tools for shoe print analysis, such as high-resolution photography and casting kits (MHA, 2022). Globally, labs are adopting ALCOA+ principles (Attributable, Legible, Contemporaneous, Original,

and Accurate) to maintain a secure digital chain of custody (Houck et al., 2023). The implementation of standardized documentation through ANSI/ASB Standard 137 (2023) is essential to ensure consistency across jurisdictions (Academy Standards Board, 2023).

Identified Research Gaps

Despite technological progress, gaps remain in population frequency databases for specific shoe designs and the establishment of national sufficiency criteria for identifications (National Institute of Justice [NIJ], 2024). Research on the persistence of individual characteristics over time as a shoe continues to be worn after a crime is still in its infancy (Sauerwein, 2024). A lack of research exists associating the number of matching characteristics with the probability that an impression was made by a common source (Sauerwein, 2024). Furthermore, most machine learning models for retrieval are trained on lab-produced prints and fail to generalize to degraded crime scene data (Jain et al., 2024). Future work must focus on developing models that are robust to the diverse perturbations found in real-world forensic casework (Jain et al., 2024).

5. Conclusion

The discipline of forensic footwear analysis has successfully transitioned from a subjective craft to a technologically advanced science. The adoption of non-destructive 3D capture and the establishment of rigorous error rates through the 2022 Noblis study have addressed scientific gaps identified by advisory bodies. For the Indian forensic community, the integration of population-specific morphological data and adherence to MHA infrastructure standards provide a robust tool for identification. Future progress depends on establishing national sufficiency criteria and expanding databases to characterize characteristic distribution (Roy, 2025). By maintaining strict digital integrity and mitigating cognitive bias, the forensic community ensures that footwear evidence remains a robust instrument in the global pursuit of justice.

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Conflict of Interest Statement

Authors Declare that there is no conflict of interest

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