

# Tech-driven Evolution in Forensic Ballistics

Isabelle Fournier\*

Department of Forensic Science and Legal Medicine Université de Lyon École de Médecine, France

## Introduction

Forensic ballistics has made significant strides through advanced computational and analytical techniques, profoundly improving the accuracy and reliability of investigations [1].

The analysis of gunshot residue (GSR) is fundamental, with recent advancements highlighting innovative sampling methods, sophisticated detection techniques like Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX), and refined interpretation strategies. Addressing the challenge of distinguishing genuine GSR from environmental contaminants emphasizes the need for robust analytical protocols [2].

Furthermore, 3D photogrammetry greatly facilitates ballistic trajectory reconstruction. This technology provides practical utility by creating precise 3D models of crime scenes and bullet paths, enhancing the visualization and accurate measurement of trajectory angles and points of origin, thus significantly improving forensic reconstructions [3].

Automated systems for firearm and toolmark identification are also rapidly evolving. Reviews focus on advancements in 3D surface imaging, correlation algorithms, and machine learning techniques designed for objective comparison and matching of ballistic evidence. Despite progress, achieving fully automated and reliable identification still presents challenges [4].

Building on this, machine learning (ML) is increasingly integrated into forensic firearm and toolmark examinations. A systematic review assesses various ML algorithms used for automating comparison processes, enhancing identification accuracy, and developing predictive models for analysis. This research also addresses limitations and future directions for these technologies [5].

Beyond digital and automated methods, understanding the physical dynamics of ballistic impacts is crucial. A comprehensive review examines various techniques for determining the angle of a bullet's impact on glass, discussing physical principles, analysis of conchoidal fractures, and computational models for angle estimation. This accuracy is paramount for trajectory reconstruction in investigations involving glass impacts [6].

Moreover, non-destructive elemental analysis of firearm components benefits from portable X-ray fluorescence (pXRF). This technique quickly characterizes the material composition of bullets, casings, and other parts, offering valuable infor-

mation for source attribution and comparative analysis without damaging evidence [7].

Improving the visualization of latent toolmarks on fired cartridge cases is key for firearm identification. Research evaluates the efficacy of different chemical reagents in enhancing these microscopic impressions left by firearms, highlighting optimal methods for evidence processing [8].

Concurrently, microscopic 3D imaging techniques are advancing forensic firearm toolmark analysis. Reviews detail methodologies for capturing and analyzing the complex three-dimensional features of toolmarks on bullets and cartridge cases, enhancing the accuracy and objectivity of firearm identification [9].

Finally, the intricate modeling of internal ballistics remains a focus, with reviews covering advancements and challenges. This includes computational fluid dynamics, thermodynamic models, and experimental techniques to understand processes inside a firearm during discharge, critical for design optimization and forensic analysis of weapon performance [10].

## Description

The field of forensic ballistics is undergoing a transformative period, driven by the integration of advanced digital, computational, and analytical methodologies. Central to this evolution is the increasing reliance on computational ballistics, which offers sophisticated tools for trajectory analysis and detailed reconstruction of shooting incidents. These tools, powered by advanced simulations and data analytics, provide a robust framework for interpreting ballistic evidence, ensuring greater accuracy and reliability in investigations [1].

Further enhancing scene reconstruction, 3D photogrammetry has emerged as a practical and highly accurate method for visualizing ballistic trajectories. By creating precise three-dimensional models of crime scenes and bullet paths, this technology significantly improves the ability to measure trajectory angles and identify points of origin, thereby refining the overall forensic reconstruction process [3].

This digital revolution is also evident in the development of automated systems for firearm and toolmark identification, leveraging 3D surface imaging, advanced correlation algorithms, and machine learning techniques to objectively compare and match ballistic evidence, aiming to reduce subjective bias and improve efficiency [4].

A significant trend in modern forensic ballistics is the profound impact of machine learning (ML). This artificial intelligence discipline is being systematically applied across various aspects of firearm and toolmark examinations. ML algorithms are actively assessed for their ability to automate comparison processes, enhance the accuracy of identifications, and develop predictive models crucial for forensic analysis. While promising, research also highlights the need to address the inherent limitations and explore future directions for these rapidly evolving technologies [5]

For instance, microscopic 3D imaging techniques are directly contributing to this analytical precision. Reviews detail the methodologies involved in capturing and analyzing the intricate three-dimensional features of toolmarks found on bullets and cartridge cases. This level of detail is critical for enhancing both the accuracy and objectivity of firearm identification processes, complementing the broader push towards automated analysis [9]

Meanwhile, the complex field of internal ballistics modeling continues to advance, with ongoing research into computational fluid dynamics, thermodynamic models, and experimental techniques. Understanding the processes occurring inside a firearm during discharge is not only vital for weapon design optimization but also for providing crucial forensic insights into weapon performance characteristics [10]

Beyond digital and computational approaches, chemical and material analysis remains indispensable. The analysis of gunshot residue (GSR) provides crucial evidence at crime scenes. Recent advancements in GSR analysis include innovative sampling methods, sophisticated detection techniques like Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX), and more refined strategies for interpreting the evidence. A key focus remains on effectively distinguishing genuine GSR from environmental contaminants, a challenge that underscores the necessity for rigorous and robust analytical protocols [2]

Complementing this, non-destructive elemental analysis of firearm components using portable X-ray fluorescence (pXRF) offers a significant advantage. This technique allows for the rapid characterization of the material composition of bullets, casings, and other firearm parts, providing valuable information for source attribution and comparative analysis without compromising the integrity of the physical evidence [7]

Furthermore, research into the visualization of latent toolmarks on fired cartridge cases is vital for linking firearms to specific incidents. Evaluations of different chemical reagents assess their efficacy in enhancing these microscopic impressions left by firearms, which are fundamental for accurate firearm identification. Such studies are pivotal in identifying and implementing optimal methods for evidence processing, directly impacting the quality of forensic investigations [8]

Moreover, understanding the specifics of ballistic impacts, such as the angle of a bullet's entry into various materials, is critical for scene reconstruction. A comprehensive review discusses methodologies for determining the angle of bullet impact on glass, encompassing the physical principles of glass fracturing, the analysis of conchoidal fractures, and the application of computational models. This provides essential data for accurate trajectory reconstruction in cases involving glass impacts, forming a holistic approach to forensic ballistic analysis [6]

## Conclusion

Forensic ballistics is experiencing a significant evolution driven by technological advancements across various sub-disciplines. Computational ballistics, for example, is enhancing the accuracy of trajectory analysis and incident reconstruction through advanced simulations and data analytics. Gunshot Residue (GSR) analysis continues to refine its techniques with innovative sampling and detection methods, while 3D photogrammetry is proving invaluable for creating precise crime scene models and ballistic trajectory reconstructions. The field is also seeing a strong push towards automation in firearm and toolmark identification, with researchers exploring 3D surface imaging, correlation algorithms, and Machine Learning to achieve more objective and reliable comparisons. Machine Learning applications are being systematically reviewed for their role in automating processes, improving identification accuracy, and developing predictive models, though their limitations are also actively discussed. Alongside digital advancements, material science techniques like portable X-ray Fluorescence (pXRF) are enabling non-destructive elemental analysis of firearm components for source attribution. Research is also improving the visualization of latent toolmarks on cartridge cases through chemical reagents. Moreover, microscopic 3D imaging is providing unprecedented detail for firearm toolmark analysis, enhancing objectivity. Finally, the fundamental understanding of internal ballistics is progressing through computational fluid dynamics and thermodynamic models, crucial for weapon performance analysis. These diverse advancements collectively underscore a concerted effort to improve precision, objectivity, and efficiency in forensic ballistic investigations.

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## Conflict of Interest

None.

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**\*Address for Correspondence:** Isabelle, Fournier, Department of Forensic Science and Legal Medicine Université de Lyon École de Médecine, France, E-mail: isabelle.fournier@univl.fr

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