

Modern Techniques in Forensic Ballistics: An Overview

Komal Yadav¹, Priyanka Negi¹, Divyanshi Tulsani¹, Jiya¹, Rupali¹, Dolchandra kumar¹, Jai Singh¹, Sneha¹

Department of Forensic Science, School of Basic and Applied Sciences, K.R. Mangalam University, Gurugram, India

Corresponding author: - Priyanka Negi, priyankasoni.negi@gmail.com

Abstract

Forensic ballistics is of utmost importance in modern criminalistics, as it provides the essential connection between the collected evidence and the courtroom. Modern Techniques in forensic ballistics involves the advanced methods (digital, chemical and computational) used to analyse firearms, ammunition and related evidence. The comparison of ballistic evidence traditionally involves the use of optical comparison microscopy to examine and compare the striations and impressions on spent bullets and cartridge casings. However, standard 2D comparison microscopy is highly subjective and can be challenged in court, especially if the evidence is fragmented or deformed. In the last few decades, there has been a great leap towards objective, automatic and mathematically defined assessment of ballistic evidence. The current trends in ballistics imaging tend to evolve around advanced 3D optical surface topography with the use of confocal microscopy and focus variation principles. These principles are based on the non-contact surface scanning technique, which allows for capturing the minute details of the striation patterns and depth of impression with sub-micron precision. At the same time, computerized identification networks, among which the most known is the modern Automatic Ballistic Identification System (IBIS), have ceased to be limited to simple visual comparison. The second research area concerns the analysis of gunshot residue (GSR) in the context of the technological progress made in this field. Although the scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX) remains the standard method of GSR detection, other analytical techniques such as laser-induced breakdown spectroscopy (LIBS) and inductively coupled plasma mass spectrometry (ICP-MS) allow for a reliable detection of non-toxic heavy metal-free primers. Despite these advancements, challenges remain regarding high implementation costs, technical complexity, fragmented exhibits, and lack of standardized global databases. Further this review aims to present the major trends in 3D digital firearms examinations, considering their application and effectiveness in practice. Adopting objective, mathematically validated 3D digital methods strengthen evidential integrity and judicial reliability in modern courtrooms.

Keyword(s): 3D Surface Topography, Automated Ballistic Identification, Photometric Stereo, Bullet striations, Cartridge Case Examination, Digital Microscopy, Image Analysis

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1. Introduction

The area of study known as forensic ballistics is a significant branch of forensic sciences that involves analysis and interpretation of firearms, ammunition, toolmarks produced by firearms, and gunshot residue (GSR). It offers the scientific connection between ballistic evidence found in criminal investigations and the subsequent processes. In traditional firearm examinations, the technique of optical comparison microscopy was predominantly employed for comparing striations on fired bullets and impressions on cartridge cases. This procedure continues to hold importance; however, conventional two-dimensional comparisons may sometimes prove to be subjective, especially in cases of damaged, distorted, fragmented, and feature-limited specimens. Ballistic examination has become increasingly important in forensics because it can help extract information from firearm-related evidence to create links between found bullets, cartridge cases, weapons, and shooting incidents. The traditional techniques based on a human expert's judgment of match may introduce the expert's bias into the case as well. The relatively new field of computational forensics attempts to overcome the human bias angle by objective analysis and statistical

probability that can withstand the arguments in a court of law (Gerules et al., 2013). With advancements in technology, forensic ballistics has moved away from traditional microscopy to incorporate techniques such as digital imaging, chemical analysis, computation, and automated comparison systems. Techniques like 3D surface topography, confocal microscopy, photometric stereo imaging, micro-computed tomography (micro-CT), and others have been investigated for more objective examinations of firearm-related evidence. Prior studies show that three-dimensional imaging should be capable of capturing detailed surface impressions of bullets and shell casings which otherwise may not be fully captured in conventional two-dimensional imaging. Scientific approaches like Congruent Matching Cells, surface correlation, and algorithms for computer-based comparisons have been developed to find out similarities between marks made by firearms. In addition, Micro-CT has shown that it is available to perform non-destructive three-dimensional examination of cartridge cases and their design. Finally, recent developments in artificial intelligence and deep learning have been used to enhance the process of finding out the marked areas of interest and

three-dimensional images of firing-pin impressions automatically with the use of computers. The advancement in modern technology has influenced the examination of GSR. Although SEM-EDX technology is still being used, other techniques such as LIBS, Raman spectroscopy, and electrochemical analysis are being looked into for their ability to allow quicker discovery and characterization in GSR analysis. Three-dimensional data can help obtain more accurate judgments, compared to the equivalent 2D representations, thanks to the larger amount of information available (Guarnera et al., 2023). These techniques should provide elemental and molecular information making faster and selective analysis possible. Still, regarding GSR interpretation, the functionality of these methods has to reckon with such factors as the type of surface, physical activity, washing, environmental conditions, and secondary transfer.

Despite the fact that technology development is vigorous, some limitations persist in terms of cost, technical difficulties, standardization, database accessibility, dataset size, damaged or non-standard evidence, and validation under usual conditions. Automated and AI technologies would benefit from having larger and diverse datasets as well as appropriate validation to be used in practice. Thus, an extensive review of modern phenomena needs to be undertaken to analyze the development of new technologies in forensic ballistics, evaluate possible applications and limitations of these technologies, point out existing gaps in the research, and define future directions for more objective, quantitative, reliable, and scientifically substantiated examination in forensics.

2. Extent Of The Review

The scope of this review is to study the recent development of modern techniques used in forensic ballistics and to understand how these techniques are improving the examination of firearms, bullets, cartridge cases and gunshot residue. For this review, we have studied previous research papers related to different modern approaches such as 3D surface imaging, digital microscopy, automated ballistic identification, machine learning, deep learning, image processing, computed tomography (CT), gunshot residue analysis and statistical methods. The application of surface topography measurement methods to the field of firearm and toolmark analysis is fairly new (Topography Measurements and Applications in Ballistics and Tool Mark Identifications - IOPscience, n.d.).

The main purpose of reviewing these previous studies is to understand how forensic ballistics has changed from traditional visual and microscopic examination to more digital, automated and quantitative methods. We review 2D and 3D imaging techniques as well as many of the algorithms used to match these images (Gerules et al., 2013). For example, several reviewed studies have focused on 3D imaging and surface topography for examining bullet and cartridge-case marks, while other studies have used artificial intelligence and machine learning for automatic comparison and classification. The review also focuses on the usefulness of these technologies in actual forensic examination. Along with the advantages, we have considered the limitations reported by the researchers, such as small sample sizes, limited firearm types, poor-quality or damaged evidence, high equipment cost, lack of standardization and the need for larger databases and further validation. Therefore, the scope is not only to discuss what new techniques can do, but also to understand how reliable and useful they may be in practical forensic casework.

3. Methodology Used

For this review, previously published research papers and review articles related to modern forensic ballistics were collected and studied. The selected papers cover different areas of forensic ballistics, including firearm toolmarks, fired bullets, cartridge cases, firing-pin marks, breech-face marks, AI-based identification and GSR analysis, 3D Surface Topography, Photometric Stereo.

After selecting the papers, each study was read and important information was extracted in a common format. For every paper, we noted the **author and year, research topic, method or technology used, main findings, limitations and references/DOI**. This helped us understand what each researcher studied and what results were obtained. For example, studies using 3D imaging were reviewed to understand how surface information can improve the comparison of ballistic evidence, while machine-learning studies were examined to understand their potential for automatic firearm classification and identification.

Then findings from the selected studies were compared and synthesized to identify common trends, developments and research gaps (Snyder, 2019). Special attention was given to whether a technique improved accuracy, reduced manual work, provided quantitative results or helped reduce subjectivity. At the same time, the limitations mentioned by the researchers were also compared. Thus, our review is

based on **collecting, reading, extracting, comparing and summarizing previous research** rather than conducting a new laboratory experiment. The purpose is to bring together the available research and understand the present development, usefulness, limitations and future requirements of modern forensic ballistics techniques.

4. Literature Review

4.1 AI, Machine Learning & Deep-Learning Approaches

The introduction of artificial intelligence (AI), machine learning (ML), and deep learning (DL) is transforming forensic ballistics by automating the comparison of microscopic toolmarks, striations, and impressions on bullets and cartridge cases with greater speed and objectivity. The study investigated the use of machine-learning methods for comparing firing-pin impressions on cartridge cases using a Siamese network consisting of two similar Convolutional Neural Networks (CNNs)(Giverts et al., 2022a).

A new 3D surface topography-based firearm evidence comparison method is proposed, particularly for cartridge cases, in which 3D surface topography can be reconstructed using photometric stereo as shown in Fig1. 3D topography images of the cartridge cases are widely used in the comparison of ballistic. (Ilker Kara, Çankırı Karatekin University , Alihan Karatatar, Hacettepe University , 2022). ML and DenseNet showed potential for automated bullet linkage. The evaluation of bullet signatures is based on 3D scans of the LEA(Mookiah et al., 2023). The GEA tend to be less discriminative(Rice et al., 2020).

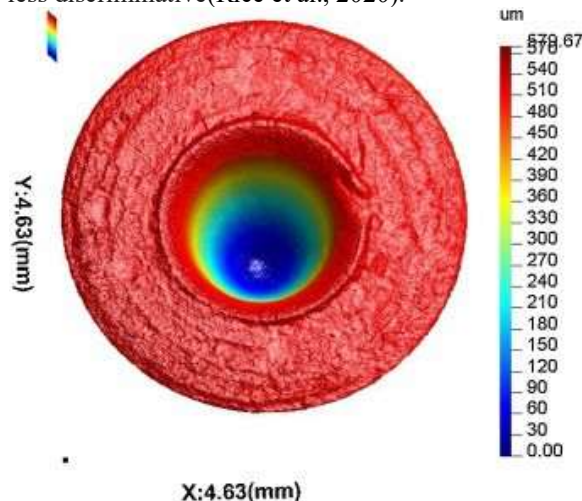


Fig1. Photometric Stereo reconstructing 3D surface topography evidence.

Artificial intelligence, machine learning and deep learning techniques can be used to automate the

comparison of firearm and ballistic evidence. But the study used only one brand of handgun and a limited number of bullets. Further, generalizability is limited because rough or handmade guns were not assessed. Also used ML and DenseNet for bullet linkage. Used air-gun pellets, not regular firearm bullets. This means that larger and more diverse datasets will be required to apply it reliably in real forensic casework. Further advantages of the proposed machine learning method are that it did not require signal alignment (of the LEA topography from the line segment), while for the deep learning approach, both signal alignment and feature extraction is not needed(Mookiah et al., 2023).

4.2 Virtual Comparison Microscopy & Automated Comparison Systems

It uses high-resolution digital imaging and computational algorithms to compare firearm toolmarks, such as bullet striations and cartridge-case impressions. 3D laser profilometry can compare the striations patterns on bullets that have been fired. As illustrated in Fig2., 3D surface analysis enables the visualization and comparison of characteristic firearm markings on cartridge cases and bullets.

A system capable of comparing the signatures on bullets in the field of firearms identification is presented (De Kinder & Bonfanti, 1999). It is based on the recording of the topography of a bullet using laser profilometry.

A total of nine test fires from each pistol slide, for a total of 90 test fired cartridge cases, were compared using confocal microscopy combined with three-dimensional cross-correlation analysis algorithms (Weller et al., 2012). Used confocal microscopy plus 3D cross-correlation to compare measurements. Got higher matching scores for comparison groups that did match than for those that didn't. There was no overlap between matching and non-matching scores in the data set. The study demonstrated breech-face mark reproducibility by providing objective and quantitative data.

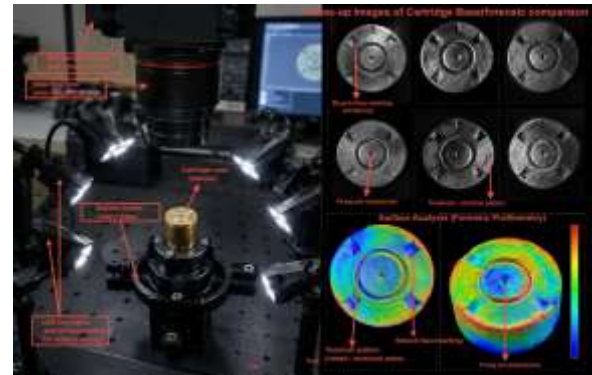


Fig2. Virtual/3D microscopy and automated comparison in forensic ballistics

Virtual/3D microscopy and automated comparison methods provide objective, quantitative ballistic measurements and show potential for improving firearm identification. The tests conducted were on a small number of firearms and samples, therefore more validation is required using a wider variety of weapons and casework samples.

4.3 Congruent Matching Cells (CMC), Statistical & Likelihood-Ratio Methods

Used 3D surface profiles and CMPS for computational comparison of microscopic surface features. The proposed method is designed to increase comparison accuracy by addressing the comparison challenges caused by striae profiles with different lateral scales, varying vertical (height) scales, and sections that are poorly marked or have little to no similarity. (Chen et al., 2019)

The congruent matching cells (CMC) method was invented for accurate breech face impression comparison (Zhang et al., 2021). It Improved CMC comparison for difficult firing-pin impressions. Estimating error rates for firearm evidence identification is a fundamental challenge in forensic science. (Song et al., 2018) CMC provided a statistical method for estimating error rates.

The improvement in the CMC algorithm involved incorporating the combination of forward and backward correlations of the cartridge case 2D optic and 3D topography images to increase the accuracy of breech face matching. The improved algorithm is tested by 780 pairwise correlations using the same optical images and 3D topography images as the initial validation. (Tong et al., 2015).

Proposed a likelihood-ratio (LR) framework for evaluating GSR findings. Instead of simply reporting the number of GSR particles, the approach considers competing propositions. Examined different levels of background GSR. Provides a more quantitative framework for communicating the evidential value of GSR. Probabilistic analysis of the GSR results provides more value to the court, so the present study calculated likelihood ratio (LR) values for finding 0-8 characteristic GSR particles (containing Lead, Barium and Antimony) on a suspect's hands, based on the available GSR data from the published literature as well as studies by the authors (Osnat et al., 2022)

4.4 Firing-Pin, Breech-Face & Toolmark Characterization

Toolmark characterization of the firing pin, breech face, and others is the examination of microscopic

marks left on cartridge cases and bullets when a firearm is fired. These marks give unique characteristics for the comparison of questioned ammunition to test-fired specimens and aid in firearm identification. The acoustic evidence combined with exterior ballistic calculations can help to determine the distance to the shooter and his position (Manolo Paredes, Jose Apolinario, 2014). But its accuracy and reliability are affected by environmental noise, recording conditions, and variations in recording equipment.

Some research into the variability of ballistic toolmarks has been conducted, however a focus of firing pin topography differences due to cartridge material variation has not yet been conducted. De Smet et al used white-light profilometry to assess the effect of primer cap seating depth on transferred toolmarks. It was found that primer cap seating depth would influence the topography of the firing pin impression, however striae patterns within breechface marks were not affected (De Smet et al., 2008).

Overall, firearm toolmark characterization provides useful data for the comparison of questioned and test-fired ammunition in forensic investigations. Modern techniques, such as white-light profilometry, can show the effects of firing conditions and cartridge characteristics on toolmark morphology. However, variability in toolmarks and the material and depth of the cartridge should be considered to ensure reliable firearm identification.

4.5 Country-Made/Improvised Firearms & Terminal Ballistics (India-focused)

This research emphasizes the importance of identifying these features and advocates for the standardization of identifiable traits (Shil et al., 2024) It states that the country-made guns have unique physical and mechanical features such as barrel length, muzzle and chamber dimensions, rifling, firing-pin features and magazine features that can be used for forensic identification.

The studies showed that standard image-processing filters can be used to trace and enhance the outer boundaries of firing-pin impressions on fired cartridge cases. This approach may help to speed up the screening and sorting of large numbers of cartridge cases and could improve the efficiency of forensic ballistics examinations while reducing manual work.

IBIS has become a tool for law enforcement and forensic laboratories (Singh et al., 2025). The study emphasizes the development of forensic ballistics in

India, including contemporary automated firearm and ammunition identification technologies like IBIS and AFIS.

4.6 CT Imaging & Bullet Fragmentation

Computed tomography (CT) may have a crucial role in the forensic documentation and analysis of firearm injuries (Oura et al., 2024). It was used to visualise bullet fragments within ballistic gelatin. It provided three-dimensional information of the distribution of fragments.

Computed Tomography Imaging can yield detailed internal structural information about ballistic specimens, allowing effective forensic examinations without subjecting the specimen to destructive analysis. Their machines may be costly, and their outcomes are highly dependent on scanning settings and specimen properties.

4.7 Gunshot Residue (GSR) Analysis

Modern air weapons are approaching firearms with their capabilities (Wilk et al., 2026). This study aims to explore the transfer and loss of GSR on commonly encountered surfaces such as ceramic, glass, metal, paper, and plastic, as well as the influence of different common hand cleaning methods on secondary transfer (Demircioğlu et al., 2024).

A study examined 63 discharged cartridge casings from Irish casework. The most frequently observed GSR compositions included: Pb-Sb-Ba-Al — about 43%. Pb-Sb-Ba — about 38%. No lead-free or mercury-containing residue types were detected in the examined casework samples.

Raman spectroscopy and LIBS were used together in sequence in an attempt to achieve the specific identification and characterization of OGSR particles from ammunition types which were closely related (Khandasammy et al., 2023). Both organic and inorganic GSR included shooter and non-shooter/background populations were studied. As shown in Table 1, the application of raman spectroscopy and LIBS was limited by the use of only three closely related ammunition types.

In the present time, the search and analysis of these GSR particles are made in forensic laboratories with Scanning Electron Microscopy/Energy Dispersive X-Ray Spectroscopy (SEM/EDX) (Lucena et al., 2011), coupled with software for the automated search of particles which allow us to select different parameters (pixels per particle, size, atomic number etc.), the definition of different classes of particle according to their composition and images of each of them in order to learn their morphology and size (Doña-Fernández et al., 2018).

Modern approaches involving techniques like SEM/EDX, Raman spectroscopy, and LIBS have improved the identification and analysis of gunshot residues (GSR) and oil-based gunshot residues (OGSR). However, ammunition type differences, surface variability, and secondary transfer effects must also be considered while analyzing such residues.

S. No	PAPER TITLE	TECHNIQUE USED	LIMITATION	CITATION
1.	Three-dimensional surface topography acquisition and analysis for firearm identification	3D surface topography-based firearm evidence comparison method	No large scale validation or comprehensive estimates of error rates are provided.	(Senin et al., 2006)
2.	Automated bullet-identification system based on surface topography techniques	3D quantitative system which captures the entire surface topography of a bullet and uses surface segmentation and feature extraction to identify firearm marks	candidate matches were produced rather than a completely independent final identification	(Xie, F, Xiao, S, Blunt, Liam, Zeng, Wenhan and Jiang, Xiang 2008)
3.	Three-dimensional surface reconstruction	3D cartridge-case topography,	Study mainly focuses on 3D data	(Ufuk Sakarya, Uğur Murat Leloğlu, Ero

	uction for cartridge cases using photometric stereo	implemented in the automated firearms identification system BALIS TIKa	acquisition, not fully automated firearm identification.	1 Tunali (2007)
4.	Automated comparisons of bullet striations based on 3D topography	Non-contact laser scanning	the identification capacity and processing speed is required further research.	Jan Kinder ^{1 a} , Monica Bonfanti ^{1 b} (1999)
5.	Real-time detection of GSR particles from crime scene: A comparative study of SEM/EDX and portable LIBS system	iForen LIBS technique	Detecting GSR depended on the size of particles and simultaneous detection of Sb, Pb, and Ba. Particles bigger than 2 µm were not completely vaporized during the LIBS testing	(Alicia Doña-Fernández ¹ , Israel de Andres-Gimeno ² , Pilar Santiago-Toribio ² , Eduardo Valtuille-Fernández ³ , Fernando Aller-Sanchez ³ , Antonio Heras-González ⁴ (2018)
6.	Quantitative Character	Micro-CT	Performed on only	(K Alsop ¹ , D Norman ² , G

	erization of Ballistic Cartridge Cases from Micro-CT		two firearms, so more data and larger databases involving multiple firearm models are needed before classification models	Remy ¹ , P Wilson ² , M A Williams ² (2021)
7.	A review of firearm toolmarks identification: Progress, challenges, and perspectives	2D morphology and CMS techniques, 3D topography using confocal microscopy, SEM and micro-CT along with CMC, deep learning and probabilistic approaches	challenge in the fusion of multimodal data, the need for explainability of algorithms, and the need for approaches applicable to a wider variety of firearms	(Yiran Xin ¹ , Yunqi Tang ² , Yaping Luo ³ , Kang Wang ⁴ (2025)
8.	Identification and highly selective differentiation of	Raman spectroscopy and LIBS	researchers have only used three kinds of	(Shelby R Khandasamy ¹ , Lenka Halámková ² , Matthieu Baudalet ³ , Igor K

	organic gunshot residues utilizing their elemental and molecular signatures		ammunition, all of which were closely related. Further research required.	Lednev (2023)
9.	Transfer and persistence studies of inorganic and organic gunshot residues using synthetic skin membranes	synthetic Strat-M® skin membranes	Controlled experiments using synthetic skin are unable to fully replicate all of the environmental and human factors encountered in actual cases.	(Courtney Vander Pyl ^a , Kourtney Dalzell ^a , Korina Menking-Hoggatt ^a , Thomas Ledergerber ^b , Luis Arroyo ^a , Tatiana Trejos ^a 2023)

TABLE 1 Summaries the discussed papers with the techniques used and their limitations.

5. Critical Evaluation

The literature reviewed indicates that forensic ballistics is slowly moving away from traditional, mostly visual comparison to digital, three-dimensional, automated and statistically supported examination. Traditional 2D comparison microscopy is still useful, as it is established, relatively accessible and provides the forensic examiner the ability to directly observe firearm and ammunition marks. However, its interpretation can be subject to the examiner's subjectivity and the examination becomes more difficult when the bullets or cartridge cases are damaged, deformed or fragmented. By applying advanced surface topography analysis, such as surface data segmentation techniques, the class characteristics and individual characteristics are effectively extracted to improve firearm identification. This system can be used as a complement for those commercial systems. The identification capacity and validity need further

research by using a large number of bullet samples in the future (Xie et al., 2009)

5.1 Advantages of Modern Techniques

One of the great strengths of modern forensic ballistics is the ability of 3D surface topography to capture depth, shape and microscopic surface characteristics that may not be fully represented in a conventional 2D image. The transition from 2D imaging to 3D scanning in the discipline of firearms and toolmark analysis is likely to provide examiners an unprecedented view of microscopic surface topography (*Development and Validation of a Virtual Examination Tool for Firearm Forensics | Office of Justice Programs*, n.d.). Using confocal microscopy, focus variation and other 3D scanning techniques, bullet striations and cartridge-case impressions can be quantified. 3D topography and Congruent Matching Cells (CMC) studies demonstrated the potential for increased objectivity in the comparison of microscopic toolmarks. The literature also shows that the analysis of 2D and 3D information combined can be better than the 2D information alone.

Automation is another great strength. Automated ballistic identification systems and computer-assisted comparison methods can search large databases and assist examiners to identify bullets or cartridge cases that may be related. This can reduce the time to search large evidential collections and may give reproducible measures. Machine learning techniques (e.g., neural networks and Siamese networks) have shown promise in comparing firing pin and other firearm marks. The results of the research show the possibility of using the Siamese network for building an objective forensic firearms examination system with a known error rate (Giverts et al., 2022b).

Modern approaches also provide an opportunity to incorporate statistical evaluation in the interpretation of firearm evidence. Likelihood-ratio and CMC-based approaches attempt to quantify the strength of evidence, rather than simply a categorical visual conclusion. This can render the rationale for an examination more transparent and possibly more appropriate for scientific assessment. However, these approaches are heavily reliant on suitable reference populations, datasets and statistical assumptions.

5.2 Limitations and Weaknesses

But modern methods have their own drawbacks. None of these tools gives us a complete match, even when they are certified by human experts. They merely provide a statistically viable match that may be used to apprehend and convict a criminal, or point to a suspect's innocence (Gerules et al., 2013). The most common limitation of the reviewed studies is the size and representativeness of the dataset. Several

machine-learning and artificial intelligence studies have been performed on a limited number of firearms, ammunition types or cartridge cases. For instance, one deep-learning study used 427 cartridge cases from just 25 firearms and four firearm models. It was reported to be high in accuracy, but the findings are limited due to the limited dataset and cannot be generalized to for different firearms and casework in the real world.

Another major limitation is the quality of the evidence. Comparison methods based on 3D and computational techniques work better when surface marks are clear and well preserved. Bullets that are crushed, bent, fragmented or otherwise heavily damaged may not contain sufficient surface information to support reliable automated comparison. The resulting missing, expanded, or distorted LEA striations can cause challenges in toolmark comparisons performed by examiners or algorithms (Chen et al., 2020). Likewise, image-processing methods may be influenced by dirt, corrosion, soot or deformation of cartridge cases. Thus, technological advances do not fully solve the problems of bad forensic evidence.

Modern equipment is costly and technically complex, further limiting widespread implementation. Advanced 3D scanners, CT systems, high resolution imaging equipment and computational infrastructure demand significant financial investment, maintenance and trained personnel. Literature specifically recognizes implementation cost, technical complexity and need for specialized hardware and software as key barriers.

5.3 Traditional and Modern Approaches: Differences

The most significant distinction between traditional and modern firearm examination is the type of information generated. Traditional 2D microscopy relies largely on visual assessment and expert interpretation, while modern 3D and computational methods can provide numerical surface measurements, digital profiles and similarity scores. A quantitative method was developed which allows to assess similarity between striated toolmarks by comparing features extracted from known toolmark samples. Finally, a comparison between estimating known match and known non-match distributions for two different types of screwdrivers suggests, that the method may be used for comparing marks of other tools as well (Baiker et al., 2014). Hence modern approaches have the potential to make comparisons more reproducible and less based on pure visual assessment.

However, the literature does not support a complete replacement of conventional examination by

automated systems. Several studies highlight that automated and 3D techniques should be used as decision support tools for forensic examiners and not as independent replacements for expert examination. Human interpretation is still required for problems involving damaged evidence, unusual or locally manufactured firearms, limited databases and variations in ammunition. For example, in studies of locally manufactured firearms it was found that automated databases may not sufficiently represent their unusual marks, thus manual examination is important. This suggests that a hybrid human-machine approach could provide better identification results than humans or algorithms alone (Cuellar et al., 2022)

5.4 Forensic importance

These developments are of considerable forensic significance as firearm evidence can provide important investigative associations between firearms, ammunition and crime scenes. Improved digital imaging can preserve detailed information from evidence, and automated systems can help search large databases for possible associations. Quantitative approaches may also enhance the documentation and communication of ballistic findings. Using these systems and an appropriately selected, representative database of firearms evidence, it is possible to estimate error rates for comparisons and obtain consistent, objective similarity scores (Ott, Thompson, et al., 2017).

Modern GSR techniques add an extra dimension to forensic investigation. SEM-EDX continues to be an important analytical technique, but methods such as LIBS, ICP-MS, Raman spectroscopy and combinations of analytical methods have expanded the possibilities for detection and characterization of gunshot residues, including residues from newer primer compositions. These findings clearly demonstrate that GSR comparison studies are meaningful but care needs to be taken when choosing suitable exhibits (Rijnders et al., 2010). GSR interpretation is still affected by background contamination, ammunition type, firearm characteristics, surface type and activity after shooting. Thus, the presence or absence of GSR should be interpreted according to the circumstances surrounding the case and not as an isolated finding.

Overall, the literature review reveals that the main benefit of the advanced forensic ballistics is its capacity to provide more detailed, measurable, and reproducible evidence. However, high precision in laboratories cannot be seen as an automatic indicator of reliability in all forensic investigations. Protocols, databases, validation, statistical models, and tests on damaged pieces of evidence are also required.

6. Research Gap

Even though modern forensic ballistics is slowly turning away from traditional optical microscopy and moving towards automated 3D surface scanning, computer algorithms, and advanced material testing, there are still several major practical problems which require serious attention.

The main problem is that the majority of the published work, for example research involving Congruent Matching Cells and Convolutional Neural Networks, depends almost completely on bullets that have been fired from standard factory-made guns under highly controlled laboratory conditions. In actual police investigations, however, ballistic evidence is very seldom in perfect condition; bullets usually strike walls, bones, or concrete and therefore leave behind badly deformed, flattened, or heavily corroded fragments in which current automated matching systems often fail. The resulting missing, expanded, or distorted LEA striations can cause challenges in toolmark comparisons performed by examiners or algorithms (Chen et al., 2020).

Another important limitation is the development of new firearms, particularly 3D-printed polymer guns, since the rifling in the barrel distorts, melts or splits after just a few shots, leading to quick changes in ballistic markings that conventional forensic databases are unable to monitor. Investigators have determined traditional firearm examination techniques are insufficient to facilitate the source printer of 3D printed firearms, instead requiring foundational research and adapted forensic methodologies that will better suit the novel toolmarks (Clifton et al., 2026). As shown in Table 1, Micro CT has been used for the quantitative characterization of ballistic cartridge cases; however, it's application can be affected by streak artefacts due to the high density of lead. Also, crime scene laser scanners have difficulty dealing with environmental disturbances such as reflective glass and indoor smoke.

Ultimately, the field has no comprehensive, open-access 3D databases and no established likelihood ratio frameworks, so most forensic examiners are unable to easily convert computational data into statistically verified evidence that normally satisfies court admissibility requirements.

7. Future Directions

In order to overcome these challenges, future research should move its emphasis from idealized laboratory conditions to more realistic, field-based forensic applications. It is essential to develop reliable and noise-resistant machine learning and computer vision systems that are capable of properly handling non-ideal evidence, such as distorted fragments of projectiles, corroded cartridge cases, and the unpredictable markings caused by locally made or rudimentary zip guns. With expansion to further

weapons, application of this methodology could complement current analysis techniques through classification models (Alsop et al., 2021). In the area of advanced imaging, efforts should be directed at improving the specialized metal-artifact reduction filters used in Micro-CT scanning, so that it becomes possible to reconstruct the internal structure of bullets and examine hidden surface striations without endangering the delicate exhibits.

Since untraceable additive-manufactured weapons are becoming more common, specific empirical frameworks must be established to examine the step-by-step thermal and mechanical wear that occurs in polymer barrels over a series of shots. Moreover, long-term studies are required to determine how firing pin impressions deteriorate after thousands of firings when different types of ammunition are used, in order to set realistic tolerance limits for automated comparison algorithms. Forensic organizations also need to work together to set up standardized, large-scale 3D ballistic databases covering a variety of weapon types, enabling experts to produce legally defensible likelihood ratios that judges and juries can easily understand. The system includes a database of 3D digital images of the bases of 10 cartridges fired per firearm from approximately 300 firearms of the same class (semi-automatic pistols that fire 9 mm diameter centre-fire Luger-type ammunition, and that have hemispherical firing pins and parallel breech-face marks (Basu et al., 2022). Lastly, the integration of portable and field-hardy analytical techniques such as rapid elemental spectroscopy for mapping gunshot residue will help make sure that evidence gathered at the crime scene is converted into consistent and quantifiable scientific proof in court.

8. Conclusion

The literature reviewed in this paper demonstrates a clear and consistent trajectory in modern forensic ballistics: a shift away from subjective, examiner-dependent 2D comparison microscopy toward objective, quantifiable, and computationally supported 3D digital methods. Studies on surface topography acquisition, photometric stereo, laser scanning, and micro-CT show that 3D data capture can reveal striation and impression characteristics with a level of precision and reproducibility that conventional 2D imaging cannot achieve. The benefit of using 3D technology is that there is no dependency on the illumination conditions and therefore consistent and repeatable measurements can be made of a surface (Ott, Soons, et al., 2017a). Techniques such as confocal microscopy and focus-variation surface scanning allow examiners to capture sub-micron detail on bullets and cartridge cases, while computerized identification networks, most notably IBIS, extend this beyond simple visual comparison into searchable,

database-driven matching. Systems like BALISTIKA and various virtual comparison microscopes illustrate how these principles can be embedded into semi-automated workflows.

However, a recurring finding across nearly all of these studies is that full automation has not yet been realized for systems generate candidate matches or quantitative similarity scores, but final identification decisions still rest with a trained examiner. The final decision whether two bullets were fired from the same barrel is still made by examiners using manual microscopic comparisons, and the ultimate determination of identity is therefore subjective (Chu et al., 2013) and large-scale validation across diverse firearms, ammunition types, and casework conditions remains limited. In parallel, the reviewed gunshot residue literature shows a similar movement toward faster, more field-deployable, and less hazardous analytical techniques. While SEM-EDX remains the established standard for GSR detection, portable LIBS, Raman spectroscopy, and ICP-MS have been shown to detect GSR particles including from non-toxic, heavy-metal-free primers with comparable reliability and considerably greater speed, making them promising for real-time, on-site crime scene analysis. Implementation of this methodology is anticipated to drastically speed up response times (i.e., from several hours per sample by standard SEM-EDS practice to a few minutes by LIBS) (Pyl et al., 2023). Complementary transfer-and-persistence studies using synthetic and human skin substrates further show that the interpretive value of GSR evidence depends heavily on surface type and post-shooting activity, which is essential for distinguishing genuine shooting involvement from secondary transfer or contamination.

Taken together, the body of research indicates that both firearm toolmark identification and GSR analysis are converging on the same broader goal: replacing subjective visual assessment with objective, mathematically validated, and reproducible evidence that can withstand scrutiny in court. Recent concerns about subjectivity in forensic firearm identification have motivated the development of algorithms to compare firearm toolmark that are imparted on ammunition and to generate quantitative measures of similarity (Ott, Soons, et al., 2017b). Yet common limitations persist throughout the literature such as small or non-representative sample sizes, high instrumentation cost and technical complexity, fragmented or deformed exhibits, lack of standardized global databases, and insufficient cross-validation across firearm models, ammunition types, and environmental conditions. Without a record of the baseline performance of the instrument, it is often hard to know when performance has deteriorated (“(PDF)

Proposed Practices for Validating the Performance of Instruments Used for Automated Inorganic Gunshot Residue Analysis,” n.d.). Addressing these gaps through larger multi-laboratory datasets, improved automation, explainable machine-learning approaches, and standardized protocols will be essential to strengthening the evidentiary integrity, judicial reliability, and courtroom admissibility of ballistic evidence going forward.

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