

A Comparative Study of Conventional and Digital Methods in Firearm Identification

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Abstract

Firearm identification is one of the important fields of forensic ballistics which includes examination of fired bullet, cartridge cases and comparison of their marks to determine whether the bullet is fired from the same firearm. Traditionally, methods such as comparison microscopy have been used to examine firearm marks and compare the features present on different evidence samples. With the advancement of technology, digital methods such as automated ballistic identification systems, digital imaging, three-dimensional surface analysis, and computer-based comparison have also been introduced in firearm examination. For this review, different research studies on comparison microscopy, automated ballistic identification, three-dimensional imaging, surface topography, automated comparison, and computer-based techniques were studied and compared. The reviewed studies show that conventional methods allow examiners to closely observe firearm marks and make direct comparisons based on their experience and examination skills. Digital methods can make firearm examination quicker and can also help in comparing images, keeping records, and checking evidence against large databases. Three-dimensional techniques can give a clearer view of the marks and surface details found on bullets and cartridge cases. However, these methods can take more time and may depend on the examiner's experience. At the same time, these methods need special equipment and software, and they also need proper testing before they can be used regularly. From the studies reviewed, it was found that more work is still needed to set common procedures, check the accuracy of these methods, and understand their possible errors. Further research is needed to assess the use of digital methods in combination with conventional methods in the identification of firearms. This paper compares both methods by discussing their working, use, advantages and limitations. The review also considers the main differences between the two methods and how they can be used together in identifying firearms.

Keywords: Firearm Identification, Forensic Ballistics, Comparison Microscopy, Digital Methods, Automated Ballistic Identification, Three-Dimensional Imaging, Surface Topography, Firearm Examination.

1-Introduction

When a firearm is fired, the parts of the firearm come into contact with the ammunition and leave microscopic markings on the fired bullets and cartridge cases. Components like the barrel, firing pin, and breech face primarily create these marks. On bullets these marks are visible as striations. On cartridge cases these marks may appear as impressed marks. By comparing the marks with reference samples, it is possible to determine whether the recovered ammunition could have been fired from a particular firearm (Puente León, 2006; Mattijssen et al., 2020). Traditionally this process has been performed by visual examination and comparative microscopy. In this approach, the examiner looks at the marks on the questioned sample and compares them with marks on a test-fired or reference sample. The examiner looks for similarities as well as differences before reaching an interpretation. Comparison microscopy is still widely used, but the result may be subjective and depend on the examiner's observation and judgement. This has resulted in discussions in the forensic study about the validity and accuracy of the firearm examination (Monson et al., 2023). There have been developments in imaging and computer technologies, thus giving rise to new methods of analyzing firearm evidence. One of the early developments was the use of digital images for automated comparison. Studies showed an automated method for comparing fired bullets in which different images were combined to represent the surface of a bullet (Changmai et al., 2019). The striation information from these images was then extracted and compared using cross-correlation. This showed that digital images could be useful for comparing firearm marks without depending completely on direct microscopic observation. Optical images and the Congruent Matching Cells method have also been used for fired cartridge case identification (Tong et al., 2014). The study investigated an automatic image analysis and identification system specifically designed for ballistic evidence. These studies helped in showing how computer-based methods could be used along with traditional firearm examination (Kara, 2016). Numerical features of firing pin impressions have also been investigated for firearm classification using statistical and geometric features (Liong et al., 2012). Another major change in firearm examination has been the use of three-dimensional imaging. Traditional photographs mainly show how

a mark looks on a surface, whereas 3D methods can also provide information about the actual shape and depth of the surface. The three-dimensional surface topography application to firearms identification was demonstrated in studies (Senin et al., 2006). Three-dimensional visualization and comparison of impressions on fired bullets has also been investigated using three-dimensional surface information (Banno et al., 2004). Automated bullet identification using a 3D laser colour scanner has further demonstrated the use of surface striation measurements for identification (Lu et al., 2014)

Studies of persistent and characteristic features in firearm toolmarks using surface measurements have been performed (Ott et al., 2017), and confocal microscopy has been used to examine breech-face marks on fired cartridge cases (Weller et al., 2012). The quantitative comparison of striated toolmarks has been studied as well (Baiker et al., 2014). Quantitative toolmark comparison methods using statistical algorithms have also been validated (Chumbley et al., 2010). The effect of different vertical and horizontal angles on toolmark comparison has been examined (Macziewski et al., 2017). These studies indicate that firearm marks can be studied not only by looking at them visually but also by measuring and analyzing their surface features. Virtual comparison microscopy is another development that has been studied in firearm examination. Duez et al. (2018) developed and validated a virtual examination tool for firearm forensics. The comparison of fired cartridge cases using 3D Virtual Comparison Microscopy was discussed (Knowles et al., 2022). Virtual tool mark generation has also been explored for efficient striation analysis (Ekstrand et al., 2014). Improved versions of tool mark comparison algorithms have further been developed to support quantitative comparison of toolmarks (Hadler & Morris, 2018). The use of 3D measurements and computer matching algorithms has also been demonstrated in firearm examination proficiency tests (Ott et al., 2017). The studies have shown that digital techniques can provide examiners an additional way of viewing and comparing marks left by firearms. They can also make it possible to store the evidence digitally and use measurements or similarity scores during comparison. In recent years, machine learning and artificial intelligence have also started being explored for firearm identification. Siamese neural network techniques were applied to compare firing pin impressions (Giverts et al., 2022). Machine learning and deep learning methods have been applied to identify bullets fired from air guns (Mookiah et al., 2023). Lightweight convolutional neural networks have been investigated for separation of striation marks from firearm bullet images (Chyrmang et al., 2024). The automated interpretation of comparison scores for firearm toolmarks on cartridge case primers has also been studied (Baiker-Sørensen et al., 2023). Deep learning has also been employed to automatically detect the region of interest in images of cartridge cases (Le Bouthillier et al., 2023). Similarity judgments of humans and machines in forensic firearm comparison analyses have been evaluated (Cuellar et al., 2022). These studies show that newer digital methods are not only being used for taking and storing images but are also being developed for automatically finding features and comparing firearm marks. Digital methods also have some practical limitations at the same time. Specialised instruments, computer software, good quality images or surface data and trained personnel may be needed. The methods also need to be properly tested and validated before they can be confidently used in routine forensic work. Additionally, the presence of manufacturing variation and subclass features can impact marks observed on firearm evidence. It has been proven that the toolmarks in cartridges are possible and that manufacturing tolerances can influence them. It proves that manufacturing associated variations can also be significant in the interpretation of firearm marks (Williams et al., 2024).). Standard cartridge cases have also been used to evaluate the use of automated ballistics identification systems for discrimination and system variation (Morris et al., 2017). Quantitative comparative methods can also be employed in the estimation of error rates for firearm evidence identification (Song et al., 2018). Thus, manufacturing variation, system performance and error rates need to be considered when evaluating digital firearm identification methods. Therefore, digital methods have useful advantages, but they still cannot be considered completely independent of proper validation and expert interpretation. Because conventional comparison microscopy is still used while digital methods such as 3D imaging, surface profiling, virtual comparison, and automated analysis are developing, comparing these two approaches is important. Conventional methods mainly depend on direct observation and the experience of the examiner, whereas digital methods can provide measurements, computer-based comparisons, and digital records. Comparing both approaches can help in understanding their differences in accuracy, reliability, processing time, efficiency, cost, documentation, and human involvement. It can also help to identify where digital methods can add value and where further improvements are still required. Feature-based comparison of 3D digital images and likelihood-ratio approaches has also been explored for fired cartridge cases (Basu et al., 2022). Virtual image standards have further been proposed for evaluating the performance of automated Congruent Matching Cells algorithms (Song & Song, 2022). The objective of this study is to evaluate the traditional and digital methods in firearm identification regarding efficiency, accuracy, time of processing, cost-effectiveness, and interpretation requirements. The study looks into the traditional methods used in firearm examination and their role in forensic work. Also included are digital imaging methods including line-scan and surface-profiling techniques used to

record and analyse ballistic marks. The study also compares both approaches in terms of accuracy, reliability, processing time, documentation, and human involvement. It also aims to understand the major benefits and drawbacks of digital approaches and to identify research gaps and opportunities for the future to improve digital approaches to firearm identification.

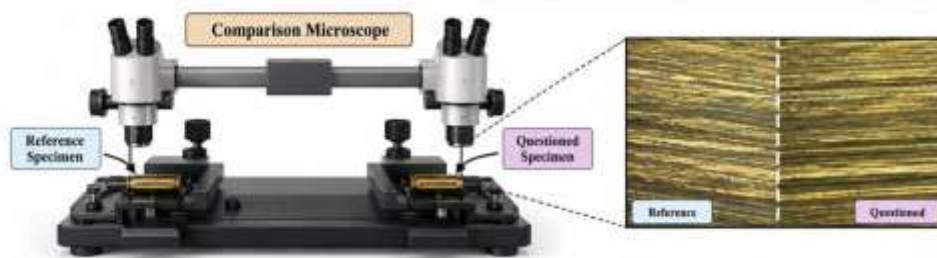


Figure 1- Comparison microscope

The microscope allows a reference specimen and a questioned specimen to be viewed simultaneously under similar magnification and lighting conditions as shown in Figure 1. It is useful in the examination of microscopic marks such as striations, as well as determining similarities and differences between specimens. Figure 2 provides a comparison between two-dimensional (2D) and three-dimensional (3D) measurements of firearm marks. In the 2D approach the surface pattern is represented as a profile and is compared by the similarity of recorded signals. Conversely, a 3D measurement captures the surface topography and thus allows the depth and shape of the marks to be taken into account in the comparison. In the example, the 3D measurements had a higher cross-correlation value than the 2D measurements, demonstrating the potential for three-dimensional surface analysis for more detailed comparison of firearm marks.

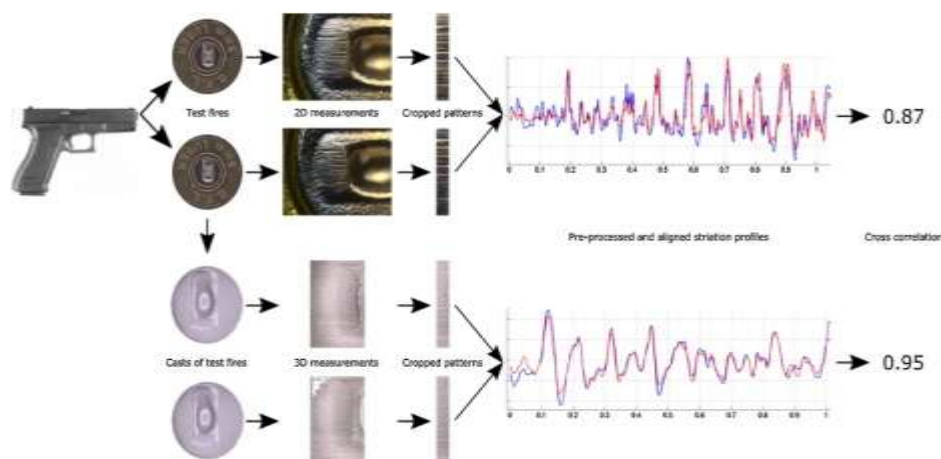


Figure 2- comparison between 2D & 3D measurement(Mattijssen et al., 2020)

2-Methodology

This review study is based on the research question of comparison between conventional and digital methods of firearm identification, their accuracy, processing speed, cost, examiner dependency and technical limitation. This study done by collection of the research papers, technical reports and journals which found from official databases of ScienceDirect, IEEE Xplore, PubMed, PubMed Central, Wiley Online Library, google scholar, NIST and OJP. During the search process these primary keywords were used like firearm identification, forensic ballistics, comparison microscope, 3D surface topography, cartridge case, bullet striations, deep learning, etc. in this review included publications time period is 1998, so that the e transition can be analyse from early automated systems to modern 3D topography and advanced AI/deep learning techniques. Specific criteria decided for literature selection, in which peer-reviewed journal papers, conference proceedings and official forensic reports which centralised on toolmark examination striation patterns, firing pin marks and breech face impressions had included, whereas non forensic firearm physics non-peer reviewed blog/news articles, duplicate records and binary option pieces were completely excluded. The selected literature was analysed using the research question and the inclusion and exclusion criteria. Initially, titles and abstracts of papers were

considered; the next step included thorough analysis of relevant papers. Papers that did not relate to firearm examination, did not cover methods of comparison of firearms based on conventional and digital images, focused mainly on other forensic techniques, or had insufficient methodological or analytic information were excluded. The resulting literature included major techniques such as conventional comparison microscopy, optical and digital image comparison, automated ballistic identification, three-dimensional imaging and topography of surfaces, quantitative tool mark comparison, virtual comparison microscopy, and machine-learning and artificial intelligence-based methods. Information about selected papers included authors and years of publication, titles of papers, the type of firearm evidence investigated, the methodology applied, the technique used for imaging or comparison, findings of the study, advantages and disadvantages, and its relevance to the current review. The results were summarized thematically without meta-analytical techniques. The techniques were compared in terms of their application, accuracy and reliability, time needed for the process, efficiency, documentation, equipment needed, and limitations. The synthesis was also used in recognizing differences between traditional and digital methodologies, as well as gaps and opportunities in combining knowledge about traditional examination techniques with digital/computational techniques in firearm identification.

3-Discussion

3.1 Conventional Methods of Firearm Identification

Conventional firearm identification mainly involves the examination of marks present on fired bullets and cartridge cases using visual examination and comparison microscopy. In this method, the examiner directly observes the marks on the questioned sample and compares them with a test-fired or reference sample. The use of comparison microscopy allows the examiner to look at the marks in detail and identify similarities and differences between the samples. The examination of breech-face marks and other firearm toolmarks has shown that characteristic features can be useful during firearm comparison (Weller et al. 2012; Ott et al. 2017). Studies have also shown that striated toolmarks can be compared by looking at measurable features, instead of depending only on what is seen under the microscope (Chumbley et al. 2010; Baiker et al. 2014).

One of the main strengths of the conventional approach is that the examiner can directly observe the evidence and consider the overall appearance of the marks. It can be applied to different types of firearm evidence and does not always require advanced digital equipment. Comparison microscopy has also been used for examining firing pin, breech-face and other impressions present on cartridge cases. However, the method involves considerable human observation and judgement. The examiner has to decide which similarities and differences are important during the comparison. Differences in examination angles can also affect the comparison of toolmarks, showing the importance of consistent examination conditions (Macziewski et al. 2017). Therefore, studies in forensic firearm examination have continued to investigate the reliability and consistency of comparison decisions.

3.2 Digital Imaging and Automated Comparison

The development of digital imaging has provided new ways of recording and comparing firearm evidence. Studies showed an automated method for comparing fired bullets in which different images were combined to represent the surface of a bullet. The striation information was then extracted and compared using cross-correlation (Puente León et al. 2006). Optical images were also used with the Congruent Matching Cells method for the identification of fired cartridge cases (Tong et al. 2014). An automatic image analysis and identification system was also investigated for ballistic evidence (Kara et al. 2016). These approaches show that digital images can be used not only for recording firearm marks but also for searching and comparing them using computer-based methods.

A useful part of digital imaging is that the evidence can be stored in digital form and examined again when required. It can also make the comparison process more systematic by using the same type of image data for different samples. Digital imaging has been applied to bullets, cartridge cases and individual firearm marks, making it useful for different stages of firearm examination (Puente León et al. 2006; Tong et al. 2014; Kara et al. 2016). However, digital comparison can be affected by image quality, surface condition and the way the images are processed. Automated systems also need suitable software and proper validation before they can be used in routine forensic examination. These requirements can make digital methods more expensive and technically demanding than simple microscopic examination.

3.3 Three-Dimensional imaging and surface tonography

Three-dimensional imaging has provided another approach for examining firearm marks. Unlike a normal two-dimensional image, 3D imaging can provide information about the shape, height and depth of features present

on the surface. The use of three-dimensional surface topography for firearm identification was investigated to obtain detailed measurements of firearm marks (Senin et al. 2006). Confocal microscopy was also used to examine breech-face marks on fired cartridge cases and study the features produced by consecutively manufactured firearm components (Weller et al. 2012). Persistent and characteristic features in firearm toolmarks were further examined using surface measurements (Ott et al. 2017).

One advantage of 3D methods is that the marks can be studied using actual surface measurements instead of depending only on their visual appearance. Quantitative comparison of striated toolmarks has also been investigated using measurable surface characteristics (Baiker et al. 2014). The numerical method of comparison of tool mark analysis has also been attempted, where numerical figures were used for measuring the similarities between the marks caused by the tools (Chumbley et al., 2010; Yang et al., 2019). It becomes all the more important if the task at hand involves quantifying the process of analysis. At the same time, 3D systems generally require specialised equipment, software and technical knowledge. The quality of the measurements can also depend on the condition of the firearm mark and the method used for collecting the surface data.

3.4 Virtual comparison microscopy and quantitative comparison

Virtual comparison microscopy has developed as another digital approach for firearm examination. The development and validation of a virtual examination tool for firearm forensic applications demonstrated how firearm evidence could be examined in a digital environment (Duez et al. 2018). 3D Virtual Comparison Microscopy was also evaluated as a method for comparison of expended cartridge cases demonstrating the use of digital firearm comparison (Knowles et al. 2022). Optical comparison microscopy and virtual comparison microscopy have also been studied together with quantitative similarity scores; to understand how digital methods can assist in toolmark comparison (Koh and Yeoh 2022).

Quantitative comparison methods can provide numerical information about the similarity between two marks. Statistical pattern comparison of striated toolmarks has been investigated as a way of making comparison more measurable (Petraco et al. 2012). Improved toolmark comparison algorithms have also been developed to increase the usefulness of computer-based comparison (Hadler and Morris 2018). Quantitative statistics have further been applied to toolmark identification and comparison (Yang et al. 2019). These methods can reduce some of the dependence on simple visual comparison and can provide additional information to the examiner. However, a similarity score by itself does not provide the complete forensic interpretation. The result still depends on the quality of the data, the algorithm used and the way the numerical result is interpreted.

3.5 Machine Learning and Artificial Intelligence in Firearm Identification

Machine learning and artificial intelligence are newer entrants into the field of digital firearm examination. Neural networks have also been used to compare firing pin marks, i.e., to demonstrate the use of computer based pattern recognition in firearm examination (Giverts et al. 2022). The air gun bullets were identified using AI (Mookiah et al. 2023). Lightweight image-processing models can also be useful to locate and isolate striation marks in images of fired bullets (Chyrmang et al. 2024). Computer analysis of the marks on cartridge case primers was performed and the results compared (Baiker-Sørensen et al. 2023).

When there are many images to check, artificial intelligence can help by looking for similar patterns in the images and save time. It can reduce the number of images you need to look at one by one AI can also help find useful features, group similar images, tell different marks apart, and compare firearm evidence. Recent studies have also used deep learning to identify the firearm brand from cartridge case images. This shows that AI is being used for different types of firearm evidence. However, the results can change depending on the quality and variety of the data used for training. Two different types of marks that can be seen in firearm and tool mark examination are shown in Figure 3. On the left side are striation marks, which are fine, usually parallel lines formed when two surfaces are brought into contact and one surface moves across the other. On the right side, there is an impression mark, which is formed when the surface of the firearm touches the cartridge case and leaves a corresponding pattern. Both types of marks can have useful microscopic features for comparison of questioned firearm evidence to known reference samples. Figure 4 shows the important regions of a fired cartridge case that may carry firearm-related marks. The area of the breech face (A) may produce impression patterns on the rear surface of the cartridge case when the cartridge is fired. The firing pin area (B) leaves a characteristic impression on the primer during ignition. These marks can be studied and compared to test fired cartridge cases to see if the observed patterns are consistent with the same firearm.

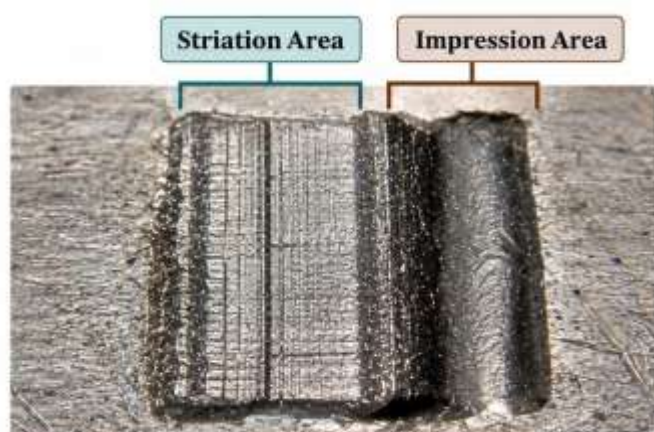


Figure 3 - left side of image shows striation marks and right side shows impression mark

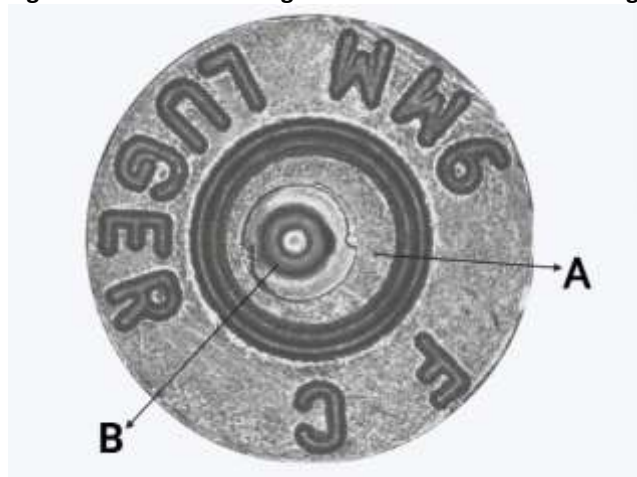


Figure 4 – A- breech face ; B – firing pin

Table 1- Comparison of Conventional and Digital Methods in Firearm Identification

Parameter	Conventional method	Digital method	Supporting citation
Basic approach	Visual and microscopic comparison of firearm-produced marks.	Digital image, surface-topography or computer-assisted comparison of firearm marks.	Weller et al. (2012); Senin et al. (2006)
Main evidence	Bullets and cartridge cases examined directly under microscopy.	Bullets, cartridge cases and their digital representations are analysed.	Puente León (2006)
Comparison basis	Examiner observes corresponding characteristics such as striations and impressions.	Uses numerical similarity, correlation, 2D/3D surface information or computational features.	Ott et al. (2017)
Bullet examination	Visual comparison of striation patterns on fired bullets.	Digital extraction and correlation of striation features and surface information.	Puente León (2006)
Cartridge case examination	Comparison of breech-face, firing-pin and other impressions using microscopy.	Optical image correlation, 3D topography and virtual comparison can be used.	Tong et al. (2014)
Data representation	Primarily microscopic/optical observation and	2D optical images, numerical features and/or 3D surface data.	Senin et al. (2006)

	photographic documentation		
Quantitative analysis	Traditionally relies strongly on examiner interpretation of observed similarities.	Can use similarity scores, correlation values and likelihood-ratio approaches.	Weller et al. (2012)
Automation	Limited automation; examiner performs the principal comparison.	Can support automated detection, comparison, segmentation and classification.	Giverts et al. (2022)
Main advantage	Established examination approach with direct visual interpretation of firearm marks.	Provides measurable/computational information and can support reproducible comparison.	Senin et al. (2006)
Main limitation	Interpretation can be influenced by examiner and examination conditions.	Requires suitable data, specialised equipment/software and appropriate validation.	Giverts et al. (2022)

3.6 Accuracy and reliability

Reliability and accuracy have an important function in the comparison of conventional methods and digital methods. Conventional examination allows the examiner to directly observe the evidence and use professional judgement during comparison. At the same time, the involvement of human judgement can introduce differences in interpretation between examiners. Research has examined the validity and reliability of forensic firearm examiner decisions and the factors that can affect comparison results. Studies have also shown that striated toolmarks can be compared using measurable features instead of relying only on visual observation (Chumbley et al. 2010; Baiker et al. 2014).

Digital methods can provide measurable data, similarity scores and computer-assisted comparisons, which may make some parts of the process more consistent. However, digital methods do not completely remove sources of variation from firearm evidence. Manufacturing differences and subclass characteristics can be present in firearm marks and may affect their interpretation (Weller et al. 2012; Ott et al. 2017). The way cartridges are made, it can also affect the marks which are left on cartridge cases (Williams et al. 2024). So, even though with digital methods, the examiner needs to understand the marks and their source before reaching to the conclusion.

3.7 Conventional and Digital Methods: Practical Strengths and Challenges

Both conventional and digital methods have their own practical uses. Conventional microscopy is useful because it allows direct examination of firearm marks and can be performed without advanced computer-based systems. It is also useful when the examiner needs to observe the overall appearance of a mark and consider different features together. Digital methods provide additional options such as image storage, automated comparison, surface measurement and statistical analysis (Puente León et al. 2006; Senin et al. 2006; Chumbley et al. 2010). Digital methods are useful when many samples need to be compared or searched. They can also reduce some of the manual work involved in checking the samples (Tong et al. 2014; Baiker-Sørensen et al. 2023). 3D methods can show more details of the surface marks on firearms. AI-based methods can also help in finding and comparing features in the evidence (Senin et al. 2006; Chyrmang et al. 2024). However, digital systems may need costly equipment, special software, technical knowhow and appropriate data. Conventional examination is simpler equipment-wise, but relies more on observation and judgement of the examiner. Both approaches thus have different strengths and challenges, and digital methods can also be used to support rather than completely replace the conventional examination.

3.8 Challenges in Digital Firearm Examination

Although digital methods provide several advantages, their practical use also has some challenges. Specialised instruments may be required for 3D imaging and surface profiling, and the systems can involve higher costs than conventional microscopic examination. Digital methods also depend on the quality of images or surface data obtained from the evidence. Poor-quality images, damaged surfaces or unsuitable data can affect the results of computer-based comparison.

4-LIMITATIONS

4.1 Incomplete and small data sets:

The main limitation of the present research is the use of relatively small and limited data sets. Many studies focus on one particular firearm model, one particular calibre, one particular type of ammunition or a small number of samples. This leaves a research gap in understanding the performance of these methods on a wider and more diverse range of firearms and forensic evidence. Such datasets may not capture the wide variation in real forensic cases. Hence, to improve the reliability and generalisability of these methods, larger and more diverse datasets with different firearms, ammunition and evidence conditions are needed.

4.2 Lack of standardisation and validation:

Digital and quantitative methods offer promise, but many techniques are still limited in their validation for routine forensic use. However, existing studies are often performed under specific experimental conditions and there is a research gap to determine if the results reported in these studies remain reliable in different samples, laboratories and forensic conditions. Another limitation is the lack of standardised procedures for imaging, analysis, scoring and interpretation. Need for more testing and standard methods.

4.3 Quality Dependency of Image and Evidence:

The performance of digital methods is highly dependent on the quality of the images and the firearm evidence being analysed. Evidence may be of poor quality, damaged, incomplete or poorly marked, which can affect image segmentation, feature extraction and automated comparison. This leaves a research gap, as many methods have not been sufficiently evaluated on difficult, damaged or poorly marked forensic evidence. Further research is thus required to determine the reliability of these methods under conditions of poor evidence quality, or ambiguous marks.

4.4 Limitations of generalisation and bias in AI-based methods:

AI and deep learning techniques usually require large, high-quality and balanced datasets to work effectively. However, several existing studies use restricted, unbalanced or synthetic samples which may introduce bias for AI models and create a research gap in their ability to generalise to different firearm evidence. Also, there are differences in ammunition barrel wear, manufacturing differences, and non-standard firearms that can affect automated comparison. Additional research using diverse and representative real-world to determine whether these models can perform consistently across different conditions.

4.5 Continued Reliance on Human Expertise

Even though the automation and digitalization techniques have been developed, still they do not constitute a complete automated firearm identification procedure. Digital tools can be used for the purposes of processing and comparing and ranking of candidates. However, verification step remains to be done manually. In this case, there is possibility for conducting more research on developing and testing procedures that will add to the existing process without eliminating expert verification.

4.6 Representation of Real-World Forensic Conditions

Another problem of the existing research relates to the applicability of laboratory experiments under real-life conditions. Evidence that may be damaged and varied by ammunition, erosion, manufacturing or specific firearms may not be sufficiently represented in the laboratory samples. In this case, there is lack of sufficient research on using these methods in practice, not just in laboratory environment. Therefore, it is necessary to conduct more tests of these methods with more complicated samples. Table 2 presents the major research gaps found in the reviewed literature. It highlights the limitations in quantitative comparison, statistical interpretation, machine learning and artificial intelligence applications and the need for further validation with diverse datasets.

Table 2 - Research Gaps Identified from the Reviewed Literature

Research Area	what previous studies show	Identified Research Gap	Supporting Citation
Conventional microscopy	Traditional light comparison microscopy is used for direct examination of firearm marks.	A structured comparison with newer digital methods is required to understand their relative methodological characteristics.	Knowles et al. (2022)
2D digital imaging	Optical images can be digitally processed and compared using methods such as	Image acquisition and representation can influence computational comparison; broader validation is required.	Tong et al. (2014)

	Congruent Matching Cells (CMC).		
3D surface topography	3D surface measurement provides additional surface information and quantitative measurements for firearm evidence.	Standardisation and broader validation across different firearm evidence are still needed.	Senin et al. (2006)
Virtual Comparison Microscopy (VCM)	3D VCM can provide virtual and quantitative comparison of cartridge-case surfaces and has been experimentally evaluated against LCM.	Further evaluation under varied firearms, ammunition and examination conditions is needed.	Knowles et al. (2022)
Quantitative toolmark comparison	Algorithms can identify persistent features and generate quantitative similarity measures for firearm/toolmark comparison.	More work is needed to establish robust comparison and interpretation across varied toolmark populations.	Ott et al. (2017)
Statistical interpretation	Firearms tool mark identification can greatly be aided by measurement and comparison methods	Appropriate reference data, statistical models and validation are necessary for reliable interpretation.	Chumbley et al. (2010)
AI / Machine Learning	Neural networks and deep-learning methods are increasingly being explored for firearm and bullet-mark analysis.	Larger, representative datasets and independent validation are needed to establish generalisability.	Giverts et al. (2022)
Overall conventional vs digital comparison	The literature contains substantial research on individual conventional and digital techniques.	A systematic comparison of conventional and digital approaches considering methodology, quantitative analysis, advantages and limitations remains an important research need.	Song et al. (2012)

5-Future scopes

- **Integration of hybrid models:** research should be done after combining conventional visual examination and AI based automated tools, that makes final decision of expert and fast screening done by AI.
- **Testing on real world crime scene data:** AI and machine learning models should train on damaged bullets, deformed fragments and real crime scene evidence not on lab fired test samples.
- **Development of explainable AI:** to make decision making process of AI systems transparent and understandable, so that AI generated matching results and LR's can easily acceptable in court of law.
- **Testing protocols to be standardized:** set uniform international guidelines and standardizes protocols for digital methods, 3D surface topography and surface profiling tools.
- **Expansion of 3D surface topography:** to make lighting independent 3D imaging techniques more cost effective and accessible, so that small forensic lab can also adopt them.

6- Conclusion

In all cases, forensic identification of firearms relied on the examination of the marks present on bullets and cartridge cases. In this respect, traditional microscopic examination has remained an important technique in the field, since it allows comparing the marks imparted to these pieces of ammunition by different firearm parts directly. All the mentioned ideas represent the basis of a forensic firearm examination in modern conditions and previous experience of its automation proves that technology can be used to assist traditional comparisons (Thompson, 2017; Hamby, 2001; Tontarski & Thompson, 1998). All three considered works reflect the transformation from traditional observations to analysis of digital images. Ballistic data can be recorded digitally and analyzed with the help of imaging sensors, line-scan imaging, and image processing methods (Chen et al., 2005; Smith et al., 2000; Li.D, 2006). Furthermore, digital processing has allowed carrying out more structured analysis of bullet markings and striation patterns and increased attention was paid to their automated extraction and classification (Pisantanaroj et al., 2020; Dutta et al., 2021). The acquisition and measurement of three-dimensional properties and topographies of the surfaces is another level of development in the examination of the firearms. There have been encouraging results concerning the usage of 3D measurements and matching algorithm in the firearm examination and proficiency testings (Song et al., 2012; Ott et al., 2017; Baruah et al., 2025). Quantitative data for the comparison have been additionally provided by means of the digital analysis of the impressions from the firing pin, breech face and other related areas. It should be noted that the usage of machine learning, artificial intelligence and computer vision have also been mentioned in the literature. Deep learning methods have been tested to classify firearms based on their bullet markings and other ballistic images. The more recent researches related to the classification of the firearms and ammunition with the help of neural networks and AI have also been conducted (Shanmugamani et al. 2015; Herke & Fedorenko 2026; Wintermans et al. 2026). The comparison of the air gun bullets with bullet holes was carried out through the application of machine and deep learning methodologies (Mookahia et al., 2023; Cardim et al., 2025; Chatterjee, 2024). Nonetheless, the literature also reveals that despite the application of digital means in examining firearms, the difficulties that characterize traditional firearms examination are not eliminated by digital means. For instance, manufacturing variations and subclasses should be taken into consideration in the interpretation of marks of firearms (Riva et al., 2017). The literature on forensics on firearm examination has also pointed out issues regarding the reliability, interpretation, and validation of firearms evidence (Bolton-King, 2016; Xin et al., 2025). Further, studies comparing similarity judgments between humans and computers reveal that the computer-based examination differs from human-based examination, thus proving that expertise is essential in forensic examinations (Cuellar et al., 2022). Furthermore, the employment of technology assists in recording and visualization of the forensics analysis process. The additional techniques involved in forensic science through the utilization of digital technology include 3D printing and virtual analysis by CT (Jani et al., 2021; Gascho, 2025). On the whole, it can be seen that the literature review points out to the fact that traditional and digital methods have their own distinct strengths. While the direct observation and interpretation are possible using conventional microscopes, digital images, measurements, automated comparison, and AI make it possible to conduct a more systematic and quantitative analysis. Automated tool marks research is being used for developing quantitative approaches to the analysis of firearm evidence (Cuellar et al., 2024).

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