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Use of different imaging techniques in stab wound analysis

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A B S T R A C T

Stab wound analysis is a relatively new field of study in forensic science, and there is currently much debate regarding the effectiveness of the analysis due to a lack of validation studies. Furthermore, the underlying viewpoints on the success of stab wound analysis vary. Examination of cut marks, for example, can reveal a variety of characteristics which can be used to determine the type of weapon that was used to inflict them. However, published studies are not consistent when identifying knife blade characteristics, instead considering a wide variety of morphological aspects and their potential value in forensic scenarios. The existing research methodology is therefore inadequate to reliably inform in such contexts, and future experimental design should be influenced by the conditional variance in stabbings in order to provide reliable findings.

The research presented here takes a systematic approach to the problem, compiling the published literature (up to September 2023) on the use of different imaging methods applied to stab wound examination to create a taxonomy to examine trends in methodological approaches in both research and investigative settings. This approach identified that published studies could be classified as either morphological or morphometrical, and further sub-classified based on their degree of success and the findings reached. This emphasises the importance of prioritising research into mark data, and the need for a multi-technique, multi-disciplinary approach. A decision tree was created to illustrate which mark attributes should be studied for which purpose, and using which imaging method(s). Furthermore, the research presented identifies two key areas in stab wound research which should be the focus of standardisation efforts, namely methodological procedures and mark characteristic collection. Knife markings are difficult to interpret, but further research and standardisation of kerf mark analysis, as highlighted here, will improve the efficiency and reliability of both forensic investigations and future experimental studies.

1. Introduction

The imprints left by a tool are referred to as “tool marks”. Whenever a tool makes contact with a surface that is dense enough, a lasting mark or indentation is created [1]. The analysis of the marks aims to identify the type of tool used in a given forensic scenario [2]. A qualified examiner/analyst may provide an expert opinion on how precisely a tool can be identified based on pattern comparisons between the mark and the suspected tool type [3]. Such analysis can take place based on the production process of the tools themselves [4,5], in which specific patterns or anomalies may become embedded in the surface of tools, and can then be linked to a tool marking left at a crime scene [6]. Patterns and anomalies in these marks are considered to be unique and may be used to identify and compare different types of tools using imaging techniques [7]. The common term used in stab wound analysis literature for a tool mark on skeletal bone material is ‘kerf mark’.

Stab wounds were first defined in 1975 as incised wounds wherein the length of injury on the surface is less than the depth of penetration into the tissue [8]. The definition was initially introduced in the context of using knives, but it can be applied to any sharp force trauma implement. The variability of stab wounds has been extensively researched in recent years in forensics, with studies tending to focus on characteristics that discriminate between different classes of sharp force weapons [9].

Weapon identification by stab mark analysis is conducted both in the skin and soft tissue as well as in bone and cartilage [10]. However, the review presented here is concerned specifically with kerf marks left on bone and cartilage, where the dimensions and shapes of the wound are better maintained due to the bone rigidity compared to skin and other soft tissue [2]. Terminology referred to within this review is defined in Table 1.

Conventional optical microscopy is most commonly used in qualitative assessments of stab wound properties [10,11], and medical CT

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Table 1
Definitions of terminology used within this study.

Term	Definition
Blunt force trauma	Tissue damage or fractures caused by the impact of a non-penetrating force
Sharp force trauma	Injuries caused by sharp objects penetrating and cutting through tissues
Weapon type	The broad classification of weapon that was used, e.g. hatchet, knife, saw
Cross-section	The morphology observed at a perpendicular to the kerf surface (for knife inflicted kerf marks, these are V-or-U shaped)
Kerf mark	Cut mark imprinted on bone by a tool characterised by narrow dimensions
Kerf property	A distinct property indicative of a general weapon type and its dimensions
Kerf floor	The base of the kerf
Kerf length	Length of the long axis of the kerf mark
Kerf morphometrics	Specified points on the kerf mark which are measured
Kerf wall	The interior surface of the kerf
Kerf edge	The outer boundary of the kerf
Kerf depth	The perpendicular depth from the floor's deepest point to the surface of the bone
Kerf shoulder height	Measured from the perpendicular height between the deepest point in the floor and the highest point on the higher edge
Kerf width	Total distance across the widest point of a kerf mark
Smooth edged blade	No teeth on the cutting edge
Scalloped blade	Rounder teeth on cutting edge for slicing
Serrated blade	Sharp teeth on the cutting edge for tearing
Striations	Parallel ridges left on the kerf wall by a blade
Tooth per inch (TPI)	Number of teeth per inch along a serrated blade

scans are most commonly used in medicolegal investigations where stabbings have occurred [12]. Many studies of stab wound analysis utilise other methods such as epifluorescence macroscopy, and SEM (scanning electron microscopy), often in combination with traditional microscopy e.g. [13].

Within the field of kerf mark analysis, there is a need for uniformity in the technical image evaluation of the mark and the conclusions derived. This applies both to case studies and laboratory-based research [10,14]. There is also limited published work that focuses on classifying the mark characteristics left by a knife blade, which includes a broad range of morphological features [15]. This study recognises that stab wound analysis sits across both archaeology and forensics, with a larger body of literature in the archaeological field e.g. [16,17]. Studying both allows closer scrutiny of all variables that have to be accounted for when analysing stab wounds.

It is important to note that the sequence of actions involved in stabbings is complex and dynamic in nature, involving numerous different movements and forces (axial and non-axial) that can be difficult to reproduce in an experimental context [18]. Other factors such as blade sharpness, the velocity of the stab, and fibre resistance are also likely to influence the kerf mark morphology and its properties.

The aims of this study were to consider both literature from forensic sources and that transferable from archaeology to i) Create a taxonomy of the language used in the area of stab wound analysis and diagnosis, which varies considerably between studies; and ii) Explain and simplify the many factors that must be addressed for experimental design when investigating stab marks. These two aims led to the production of a taxonomy flowchart (or 'decision-tree') and tables that cover the following; imaging techniques, weapons used, whether the study was based on mark visual morphology or morphometrics [19,20], the most common mark properties, and how the stab wound was inflicted [9,10].

The nature of the nomenclature made it difficult to group the results provided by the authors into broader clear themes for analysis and comparison. Therefore, the categorisations used are based on available information [2,21] and have been organised through logical reasoning drawn from the authors' conclusions, as detailed below.

2. Methods

The process of searching the literature for relevant publications for this study and subsequently creating a taxonomy to illustrate which mark attributes should be studied for which purpose in stab wound analysis, using which imaging method(s), was undertaken in 6 stages, as follows:

Stage 1: Published research articles were identified by searching the following 6 databases: Science Direct, PubMed, Microsoft Academic, Scopus, Google Scholar, and Science.gov. The search filters were set to include meta-analyses, controlled trials, reviews, systematic reviews, research papers, and case studies. The date slicers were set from 01/01/1980 up to 15/09/2023 (when the review took place). The search on Microsoft Academic was only run up until 10th December 2021, after which the engine was no longer updated.

The aim was to collect all forensic and archaeological papers that would assist in answering the question of how imaging techniques are used in stab wound analysis. Medical computed tomography (CT), micro CT, SEM, photography, optical microscopy, digital microscopy, and epifluorescence macroscopy are the most widely used techniques in stab wound analysis, therefore this study focused on these techniques as the prime method of imaging and the imaging techniques. Further criteria specified that these techniques were applied to stab wound analysis, specifically the analysis of kerf marks on bone. The criteria were deliberately kept broad to represent all available research fairly and to minimise any bias because there are many similarities between all of these contexts regarding the methodology used and the interpretation of data.

Hence, searches were defined to maximise the chances of finding relevant papers by using:

("CT" OR "SEM" OR "microscopy" OR "epifluorescence") AND ("blade characterisation" OR "stab wound" OR "knife mark") AND PUBYEAR > 1979.

It was also specified that the keywords needed to be in either the abstract or title.

Stage 2: The titles from all 6 searches were exported and combined, and all duplicates removed. All review articles were subsequently checked to identify any potentially relevant publications that had not been picked up from the database searches, but no articles of relevance were identified through this cross referencing.

Stage 3: The remaining papers were then manually reviewed to ensure the content was relevant for this study i.e. was the context set within a peer reviewed valid experiment that included sharp force trauma marks (such as those made by a knife, sword and hatchet for example), and/or had any of the imaging techniques that were set in the original search criteria been used to capture the kerf mark(s)?

If either of these topics were covered then the paper was deemed relevant and was included for further review. Each paper was then reviewed according to the following 7 criteria:

1. Do any of the imaging techniques capture kerf mark(s)?
2. Does the article contain a description of kerf mark(s)?
3. Is this a research of sharp force trauma carried out in the field of either forensics or archaeology?
4. Is there an experimental design explaining how the kerf mark(s) were created on the bone?
5. Does the article address detecting kerf mark(s) in bone or soft tissue?
6. Does the article discuss tool marks on bone?
7. Is this a case study where imaging of the skeletal trauma has been included?

Stage 4: A further review was then undertaken of all the articles which were found to match at least one of the 7 criteria in stage 3 to identify those which contained information on all of the following points:

1. An experiment using an imaging technique that has been outlined by this study and provides kerf mark characteristics in the results.
2. Details of the tool used to create the kerf mark, how the wound was inflicted, results of the study, and whether the analysis was carried out with standard visual morphology or morphometrics.
3. At least one kerf mark created in the experiment was produced by sharp force trauma

Stage 5: Due to variations in the nomenclature used in different contexts, information from the remaining literature was categorised in order to provide a clear taxonomy of terminology and procedures that could be utilised to standardise future experimental design. The remaining eligible articles were categorised across two spreadsheets with the objective to create data points for the analysis. The first categorisation addressed the experimental design and resulted in the following fields:

1. Journal of publication
2. Author & date
3. Title
4. Imaging technique
5. Weapon used
6. Based on morphology or morphometrics
7. Kerf inflicted
8. Result
9. Conclusion band

The second categorisation specifically addressed the kerf mark profiles themselves and which imaging techniques were used to identify them. Whether a characteristic was observed is attributed to all the techniques used to draw the conclusion rather than compartmentalising the different techniques outside of their original context. The fields were as follows (with kerf mark features illustrated in Fig. 1):

1. Author & date
2. Imaging technique
3. Wall & edge morphology
4. Width
5. Floor
6. Shoulder height
7. Angle
8. Cross-section profile
9. Striations
10. Length
11. Depth

Stage 6: These articles were used to construct a taxonomy to identify the most suitable imaging technique to record and/or investigate each mark property, depending on the rationale for the study. 'Conclusion bands' were developed from manual text analysis, identifying recurring themes and patterns between authors' conclusions, and considering the phrasing and terminology used in the original publications, based on the work of Love [2] and Tennick [21].

Subsequently, a structured taxonomy of the conclusions could be constructed and insight could be gained into the significance of the results and how they varied between studies. Different levels of inference were established (based on those defined by [21]) from the level of precision that is noted in the interpretation of the kerf mark.

3. Results

The initial search of all 6 databases (stage 1) identified 6396

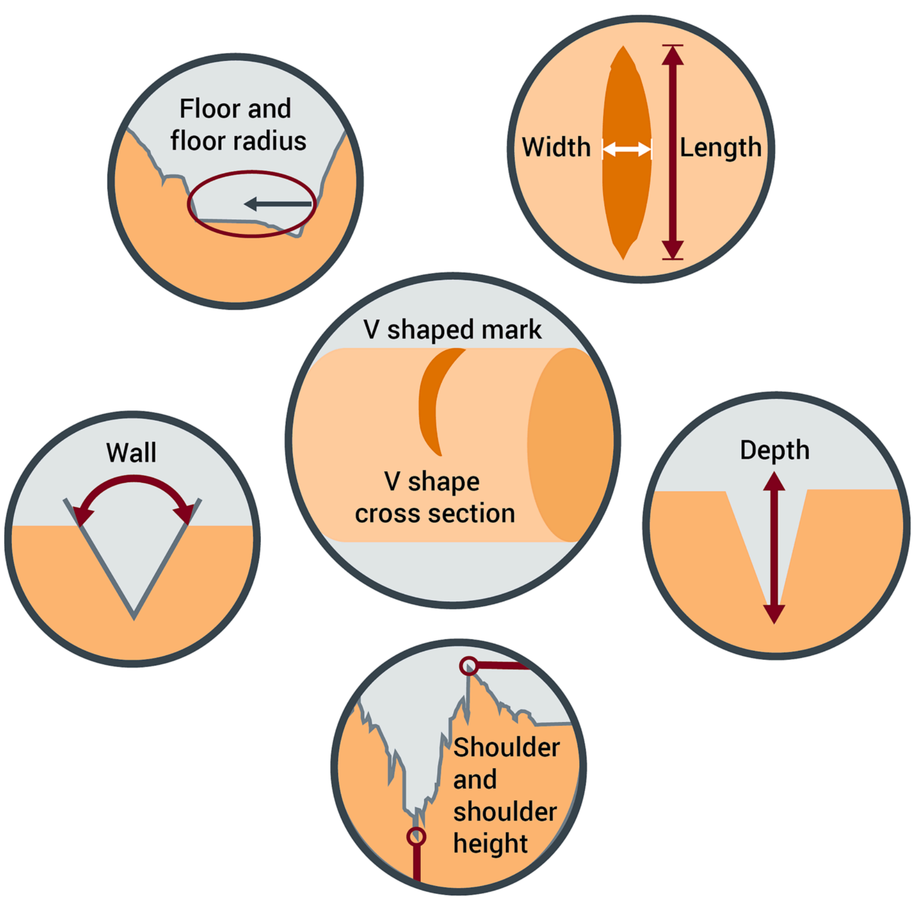

Fig. 1. Visual representation of kerf mark characteristics.

potential publications for inclusion in this study, but this number reduced to 2650 once duplicates had been removed (stage 2). Eligibility screening (stage 3) identified 270 articles and theses for further consideration, but once the final screening criteria had been applied (stage 4), only 45 publications remained for the detailed analysis required to construct the taxonomy (Fig. 2). Although this number may seem low considering the original number of articles returned from the database searches, it was important to apply such stringent inclusion criteria to ensure the final taxonomy and decision tree were as reliable and accurate as possible.

Google Scholar returned the most results for the initial search, followed by Science Direct, with many articles identified in both databases. Science Direct provided more (potentially) relevant articles, but Google Scholar identified Masters and PhD theses that Science Direct and the other search engines did not. Scopus found more articles that were not returned by the other engines, but most of those were not deemed to be relevant to this study once the eligibility criteria were applied, and those that were had also been identified by Science Direct.

The results of the categorisations according to experimental design and kerf mark properties/imaging techniques used (stage 5) that were used to construct the taxonomy and decision tree are presented in Tables 2 and 3, respectively, in the Supplementary Information.

While interpretations of kerf marks vary between research projects and case studies, each outcome could be categorised into one of four inference levels using the conclusion bands in Table 2 (SI); these are summarised in Fig. 3. The figure demonstrates that the accuracy of the conclusion drops as the levels move from green (top) to red (bottom).

The data collected from summarising the 45 published articles was then screened to identify differences in morphometrical and morphological inferences (Table 3, SI). These results were further subdivided

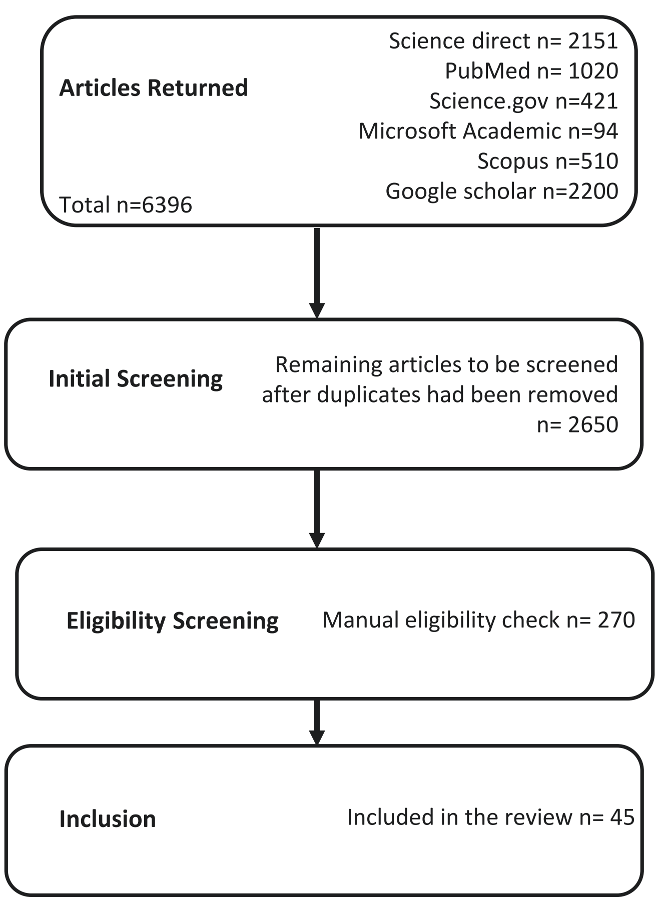

Fig. 2. The screening process for identifying applicable literature to be included in the review.

according to the imaging technique(s) used. It is essential to emphasize that studies employing combined methods were not counted twice in their respective categories. Each papers' approach for assessing the properties of a kerf fell into two main categories: morphological visual assessment (i.e. looking at the generic shape of the mark) or metrical (i.e. using quantitative geometrical markers for each kerf property and references to their significance). This distinction helped inform the research's methodology and conclusion. The distinction allowed for comparison of the effectiveness of these two approaches to ascertain if any discernible differences in outcomes existed. Of the 45 articles that were reviewed, 21 used morphometrical means, 11 used morphological means and 13 used combined methods (Fig. 4).

The choice of imaging technique depends on the research context or goal, as well as cost and availability of facilities [15,22]. Figs. 5 and 6 show the most popular imaging techniques used in the studies considered for this review, and the most popular imaging techniques over the last decade, respectively.

For papers employing morphological assessments Fig. 7 illustrates that optical microscopy was the predominant imaging technique employed, being utilized in 26 (33 %) instances among all the reviewed papers. Notably, the prevailing conclusion band within this context pertained to the distinct variation between smooth-edged and serrated blades. This was discerned in 22 (28 %) instances, with 9 (12 %) of these instances utilizing optical microscopy. A noteworthy secondary trend within this group was the variation of kerf mark properties under different conditions, which was documented in 16 (36 %) instances, with 9 cases relying on digital microscopy.

Photographic techniques provided a more evenly distributed presence across various conclusion bands and failed to yield sufficient data points to establish discernible trends.

In contrast to the morphological studies, those using a morphometrical approach (Fig. 8) exhibited greater diversity in imaging techniques and conclusions. Photography emerged as the most employed technique, featuring in 35 instances, closely followed by optical microscopy with 29 instances. Among these studies, the prevailing conclusion was the variation of kerf marks under different conditions, predominantly observed through optical microscopy (10 instances), digital microscopy (9 instances), and photography (7 instances). The second most frequent observation involved variation between weapon types, as identified by photography (8 instances) and optical microscopy (9 instances).

In the subset of papers combining morphology and morphometrics (Fig. 9), optical microscopy featured prominently, being employed in all 45 instances, with a specific emphasis on differentiating between smooth-edged and serrated knives in 28 instances. Furthermore, optical microscopy was commonly used in this context to investigate kerf mark variation under different conditions; this was noted in 12 instances.

Fig. 10 demonstrates the distributions of the kerf mark properties observed, and how often they were reported by a paper, while Fig. 11 shows the most popular technique when aiming to identify a specific kerf mark property (as illustrated in Fig. 2).

Among the common attributes examined, width emerges as the most frequently studied, observed in 23 instances, closely followed by striations, which are noted 20 times. Cross-section profile, although slightly less common, is still examined in 19 instances. Notably, photography and digital microscopy stand out as the most well-versed techniques for capturing a wide variety of attributes, suggesting their effectiveness in documenting the intricacies of blade edges in this body of research. This data underscores the significance of width, striations, and cross-section profile in blade edge analysis and highlights the adaptability of different imaging methods in exploring these characteristics.

Medical CT appears to be a less popular technique, with limited representation in the studies, indicating that it is not commonly utilized for blade edge analysis within this dataset. This observation emphasizes the preference for other imaging techniques in this particular area of research.

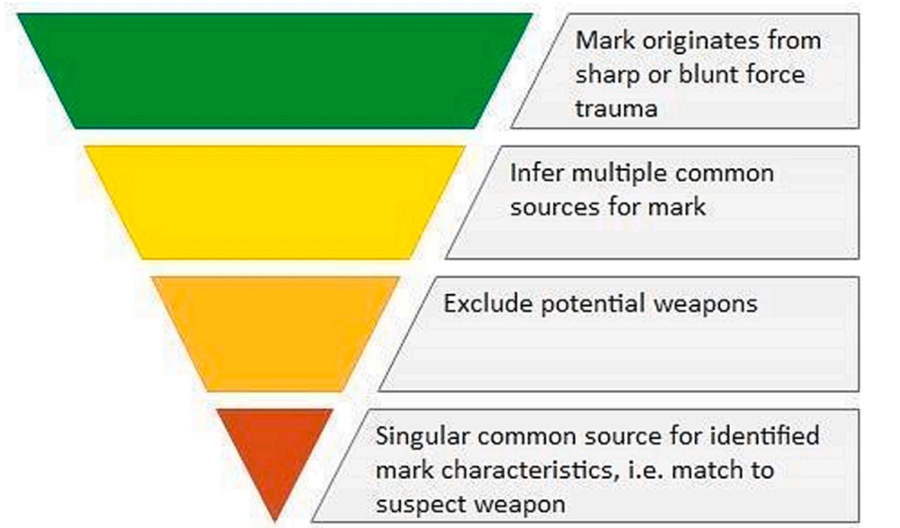

Fig. 3. From top to bottom, the steps here show the decreasing precision in the conclusion in kerf mark analysis.

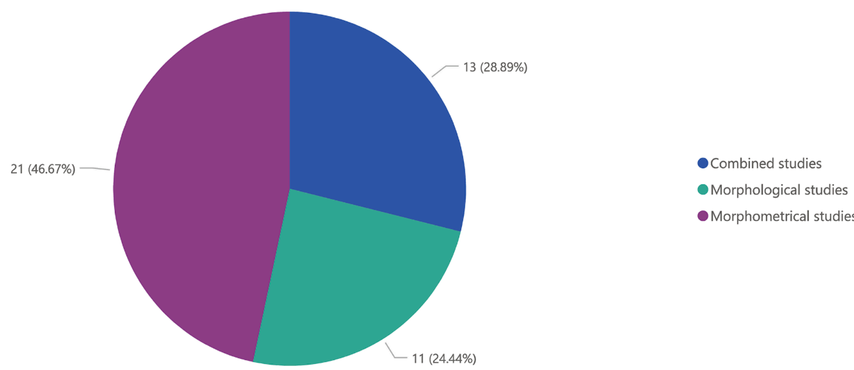

Fig. 4. Number of articles which applied morphological or morphometrical techniques, or a combination of both.

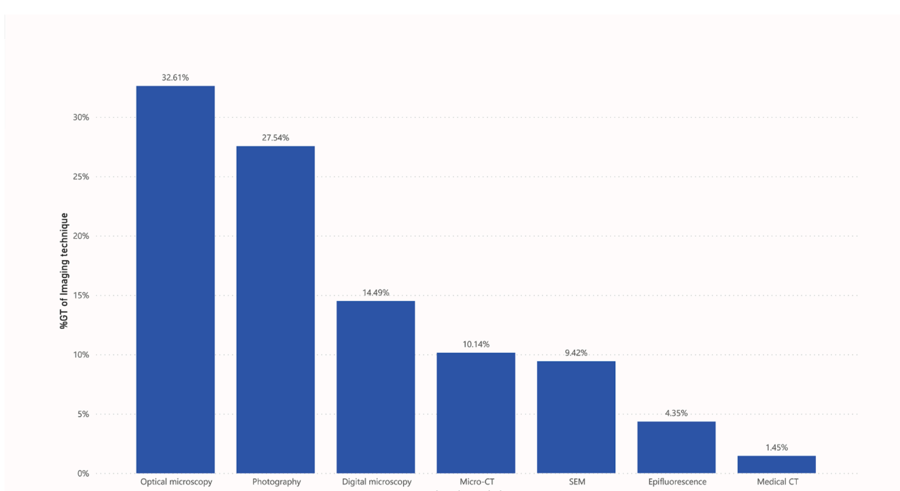

Fig. 5. Percentage of papers in this review using each imaging technique.

Over the past decade, the data from stab wound analysis studies reflects a relatively consistent distribution of imaging techniques and number of papers published. While the utilization of various imaging techniques such as optical microscopy, digital microscopy, and photography has remained consistent, there have been peaks in activity within this field around the years 2017, 2018, and 2020 (Fig. 6). These peaks suggest potentially heightened interest and research activity in this field during those years (although no studies from 2019 met the criteria for inclusion in this study). SEM has notably declined in usage over the last five years, indicating a shift away from this technique in favour of other methods which may offer more accessible and versatile options for researchers. Overall, the data reflects a dynamic landscape,

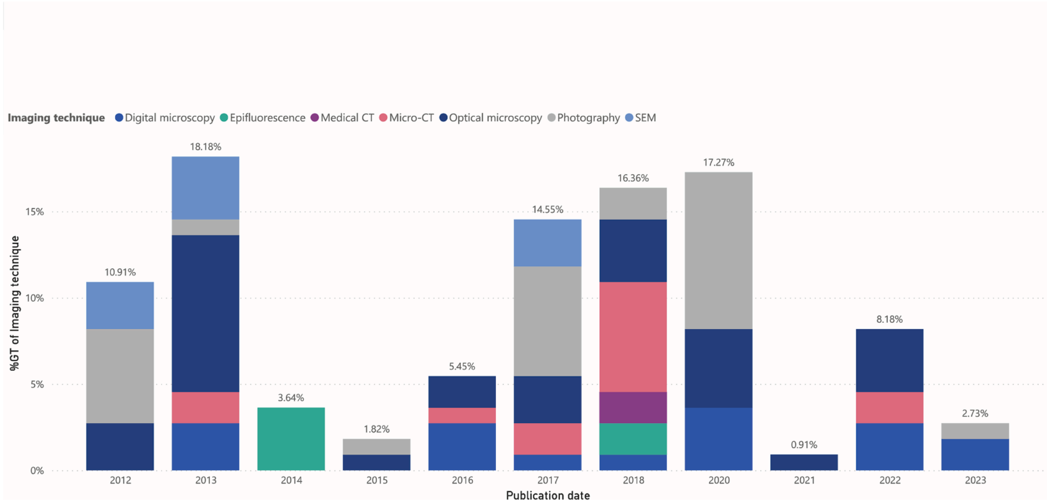

Fig. 6. Percentage of number papers and imaging techniques used by publication date since 2012. No studies from 2019 matched the criteria for inclusion in this study.

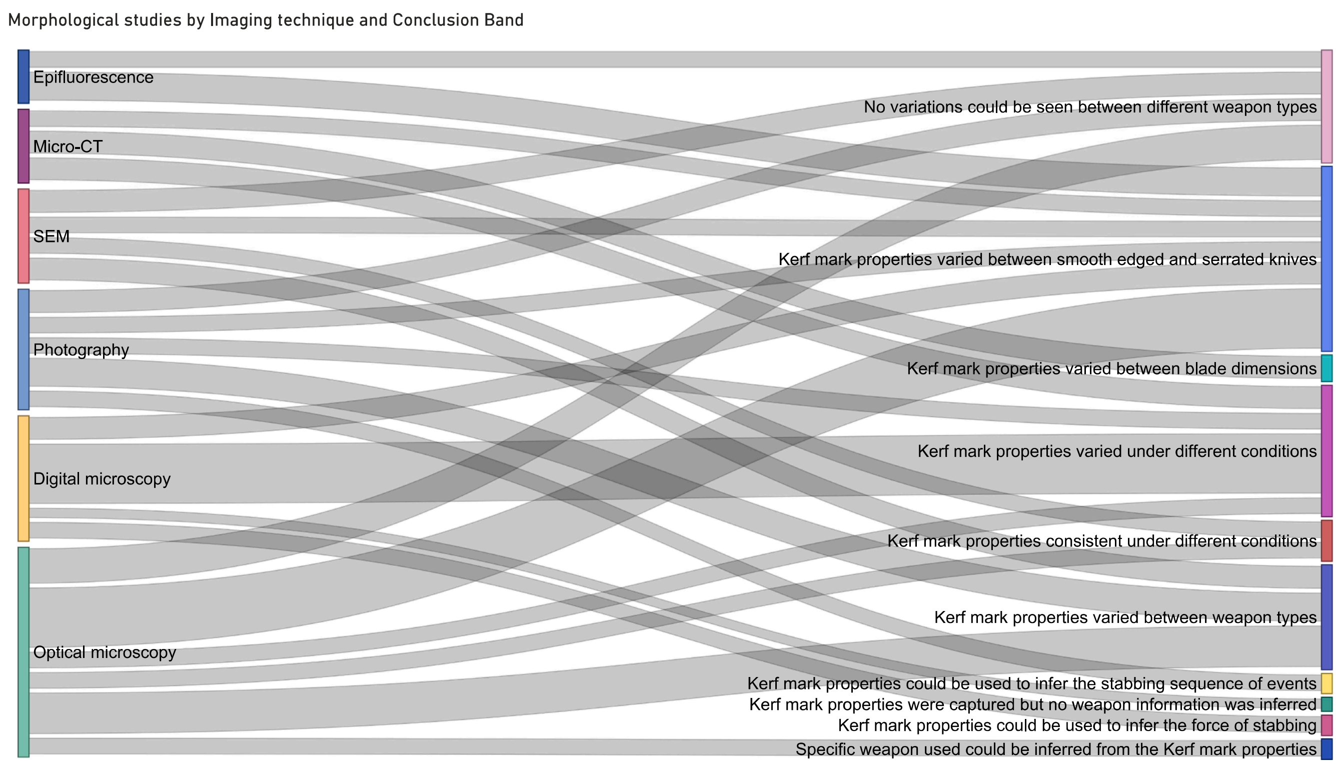

Fig. 7. Morphological studies by imaging technique and conclusion band.

with evolving preferences in imaging techniques over the past decade.

Fig. 12 presents a decision tree developed from the data presented in Table 2, outlining the process from obtaining a kerf mark to evaluating its characteristic, information (see Table 3, SI).). The flow prioritises mark variations with strong discriminating values and aims to assist future researchers in reducing mistake variability. It will also assist the analyst to navigate the decision-making process and reach the most likely and probable findings.

4. Discussion

The results of this analysis indicate that for research in stab wound analysis to be effective, more effort is required to build a precise, proven approach and elucidate the larger implications of synergistic science [10]. Stab wound analysis should follow a context-based approach in which known factors from cases are utilised to construct an experimental design for testing under similar (or nearly identical) circumstances. As such, it is important that researchers choose the imaging technique that best records the mark's characteristics whilst taking into consideration the invasiveness of the chosen method against ethical issues and the quality of the mark [23,24].

The results demonstrated that the different imaging approaches have different levels of accuracy and could impact the identification and interpretation of kerf marks significantly. Furthermore, the existing deficiency of focused research in this domain, particularly regarding the classification of characteristics left by knife blades, which encompass a

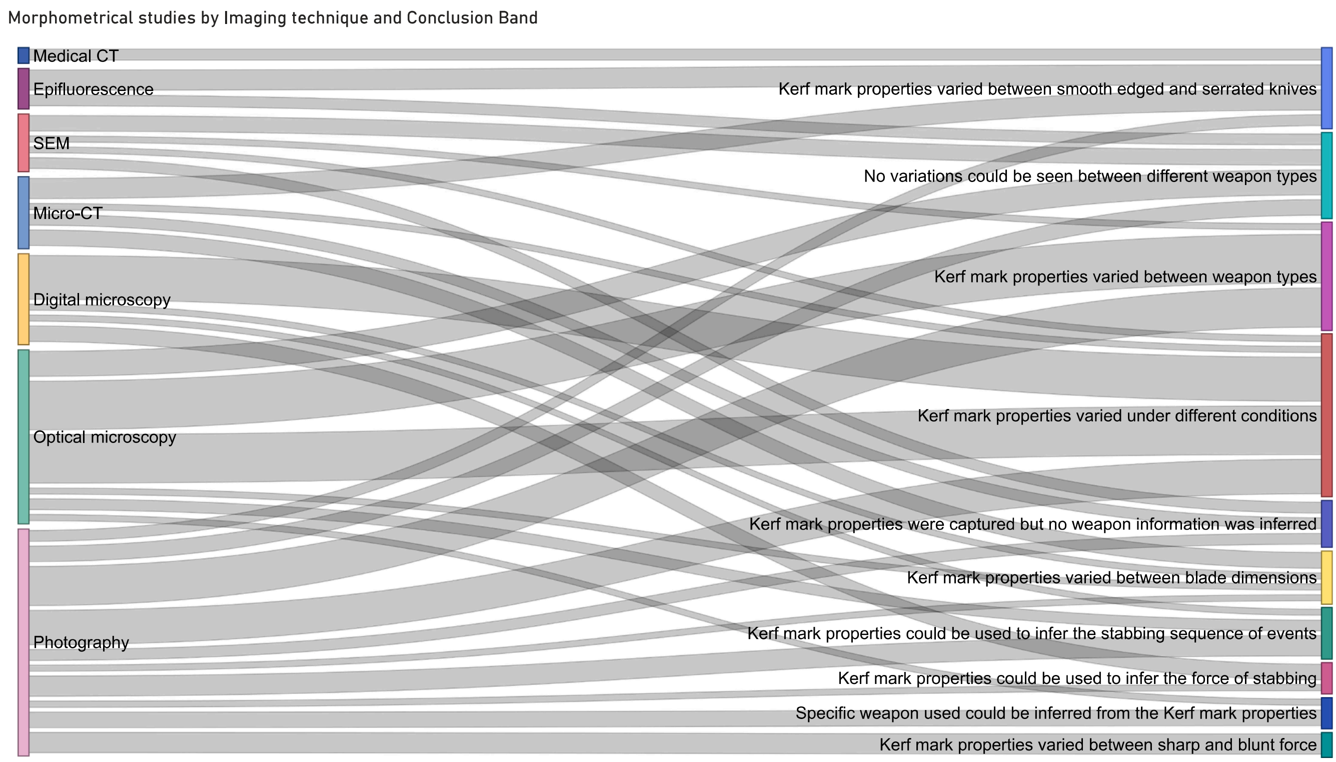

Fig. 8. Morphometrical studies by imaging technique and conclusion band.

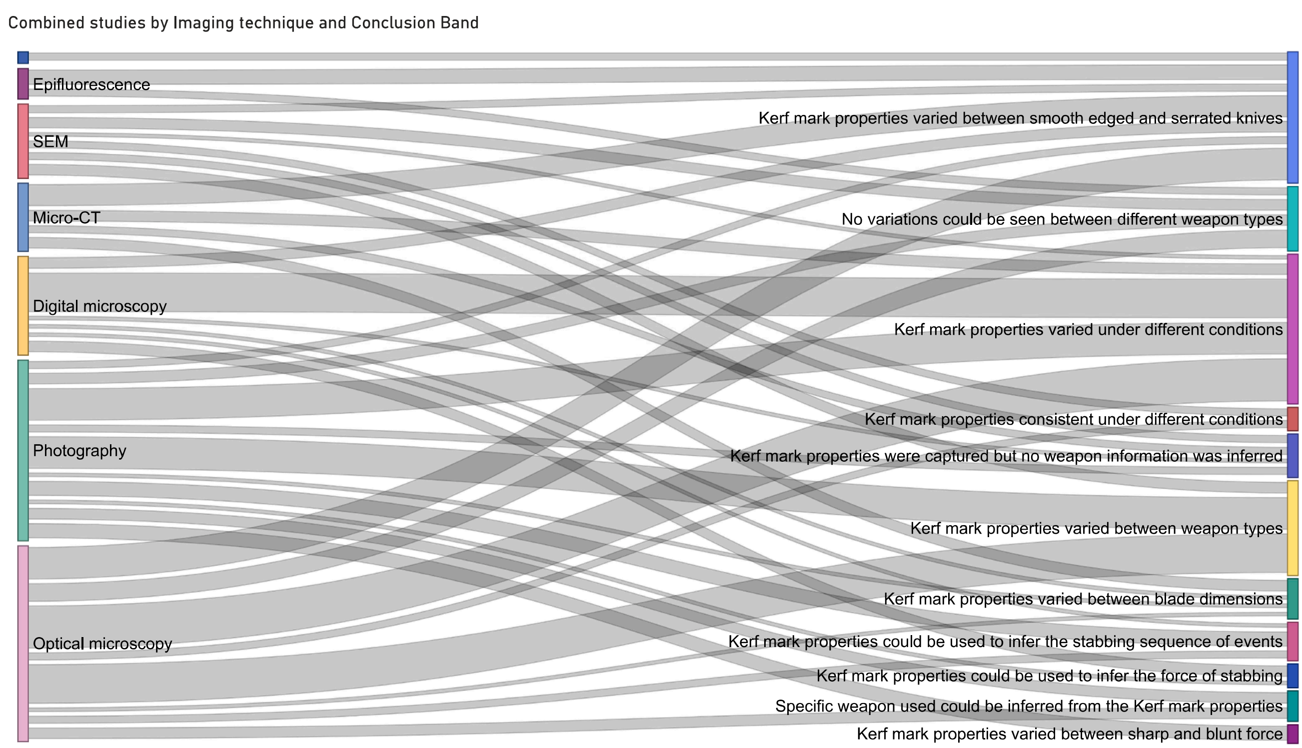

Fig. 9. Combined morphological and morphometrical studies by imaging technique and conclusion band.

diverse array of morphological features with potential forensic significance, underscores the need for dedicated studies. Efforts to standardize methodology protocols and mark profile acquisition are imperative to address the complexities inherent in stab wound analysis. It is worth noting that while morphological analysis provides insights into injury mechanisms, geometrical (morphometrical) analysis focuses on the precise measurement of angles and dimensions, hence the two approaches offer complementary perspectives. Furthermore, the inherent challenge in interpreting knife blade marks highlights the necessity for further research to comprehensively assess the variations in mark characteristics.

Table 2 and Fig. 12 provide a clear view of what might be expected

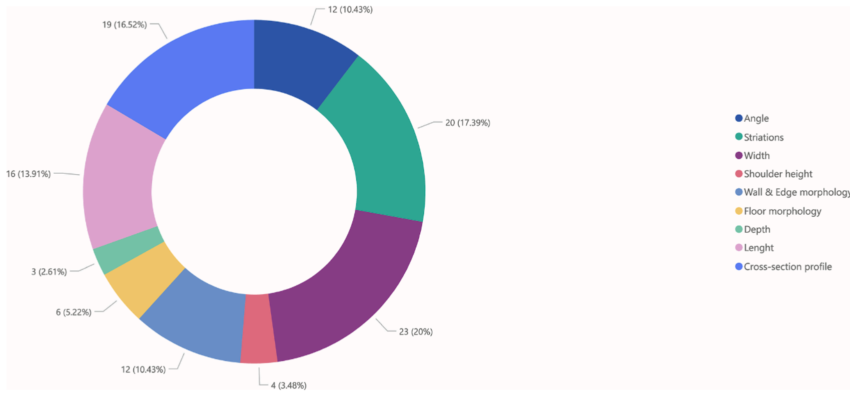

Fig. 10. Distributions of kerf mark properties and how often the terms are reported.

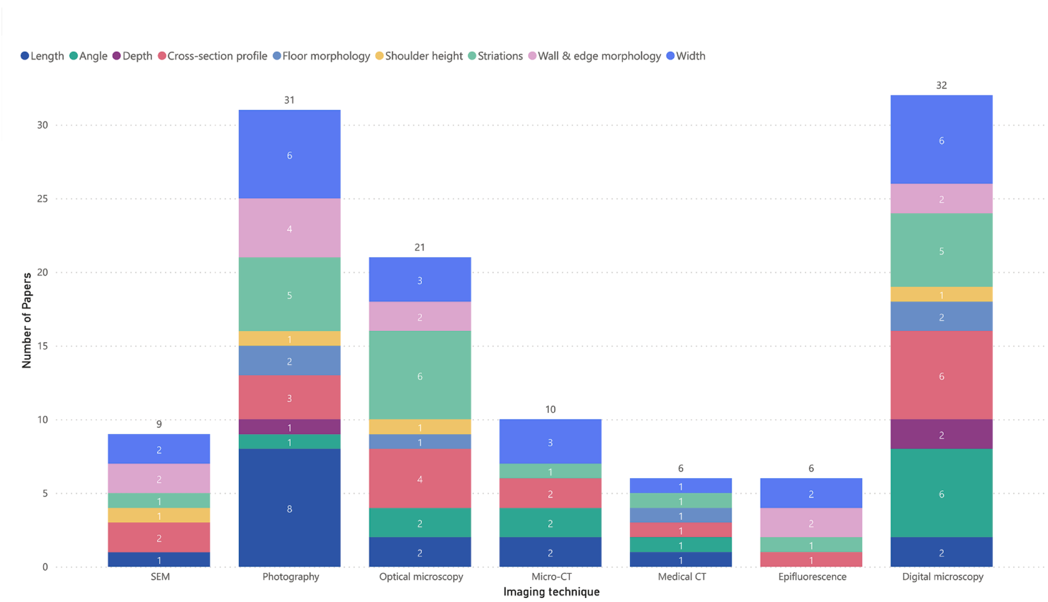

Fig. 11. Identification and frequency of techniques applied to identify specific kerf mark properties.

for a given technique based on published studies. They also indicate that if a multi-method approach for a study is desired, which features can be determined using more cost-friendly methods, and which require more sophisticated and/or expensive techniques. There are arguably differences between what mark variants are frequently noted as being of assistance in identifying a weapon. However, further investigation into the accuracy of these marks regarding how frequently they are recorded in observations is needed; it would be interesting to see if such frequency studies correspond with the degrees of significance that current research is attributing to the characteristics.

The goal in kerf mark analysis is to arrive at as accurate a conclusion about the weapon as possible, and examining the kerf mark allows one to obtain an inference into the weapon's overall type and proportions. While interpretations vary widely between research and case studies, in Table 3 (SI) each study could be classed as falling into one of the one of four inference levels, based on their interpretation of the results; this has been illustrated in Fig. 3, showing each step increasing in its precision regarding the kerf properties' unique variants. As the precision increases from green to red, the number of validation studies on the subject decrease.

In stab wound analysis, particularly in medicolegal cases, lower levels of inferences play a pivotal role in determining critical aspects of an investigation. One such well-recognized practice within this domain involves discerning whether a mark or injury was inflicted by a sharp or blunt weapon [25]. This distinction is paramount in understanding the nature of the incident and often holds significant legal implications, as forensic experts employ well-established criteria and characteristics associated with sharp-edged or blunt weapons to draw conclusions. This practice is widely accepted as a cornerstone of forensic analysis.

There is also a recognised acceptance for interpretation of stab marks to estimate the level of force applied by the assailant and the sequence of events during the attack (e.g. victim-assailant positions and movements) [3]. However, with exponential advancements in imaging techniques over recent years, much research has shifted to studying the variability between kerf marks created by different weapon types through observations of morphological and metrical markers on the kerf [26].

In forensics, observations such as these have significant implications for both ongoing investigations and evidence presentations in court [14]. It is possible to obtain confident conclusions relating to the general weapon type from examination of a kerf mark, and quite possible to estimate its dimensions. In the literature, the confidence in estimating the blade dimensions has been accumulated by validating imaging techniques in the field (in particular medical CT, microscopy, and photography), and studying the cross-section profiles, walls, and floors of a kerf mark has been shown to provide further insight into the type of sharp weapon [11,18,27–31].

Many studies focus on characteristics that can distinguish between serrated and smooth-edged knife blades. Capuani et al. [32] examined

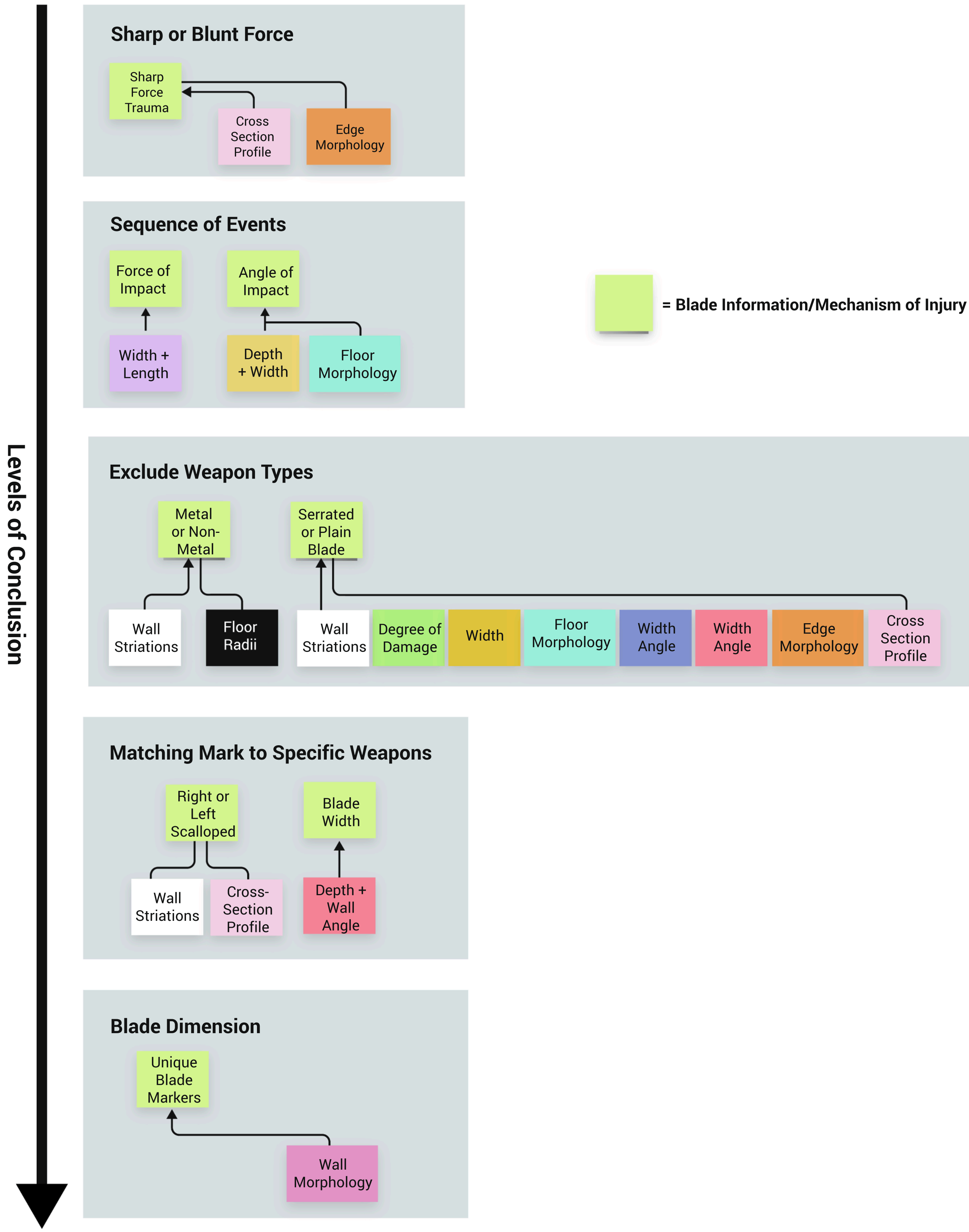

Fig. 12. Decision-tree illustrating the characteristics that can be used to obtain specific information.

striations and hypothesised that wall striations left on the bone could be used as markers to identify whether a blade was smooth or serrated. Crowder et al. [11] took this hypothesis further in their study which aimed to validate sharp force trauma analysis in bone and attempted to standardise the error rates associated with misclassification. Using digital microscopy to examine kerf marks, their data suggested that while striation patterns could be used as a distinguishing feature, teeth distance could not, as the angle of impact would influence the distance. Therefore, as the blade moves, the angle will continuously change and so will the striations. However, the same pattern will remain despite the changes in movement.

When it comes to scrutinizing striation patterns and discerning

Table 2
Which imaging techniques can be used to observe which characteristic of the kerf mark: each tick highlights which characteristics can be seen by the specified imaging technology.

Kerf Characteristic	Optical Microscopy	SEM	Photography	Micro-CT	Medical CT
Cross-Section	✔	✔	✔	✔	✔
Edge Morphology	✔	✔	✔	✔	
Width + Length	✔	✔	✔	✔	✔
Depth + Width		✔	✔		✔
Floor Morphology	✔				
Wall Striations	✔	✔		✔	
Width	✔	✔	✔	✔	✔
Width Angle	✔				
Depth + Wall Angle		✔		✔	
Floor Radii	✔				
Wall Morphology		✔			

morphology disparities between smooth and serrated blades, while traditional photography proves invaluable, its capacity to capture the full spectrum of striation patterns remains constrained by inherent limitations in detail and resolution. To overcome these constraints and delve deeper into the subtleties of blade characteristics, forensic analysts turn to a range of sophisticated imaging methods. Epifluorescence macroscopy, for instance, amplifies the visibility of intricate features using fluorescent dyes or stains, shedding light on imperfections that may signify the distinct attributes of serrated blades. Optical microscopy offers high-resolution examination, enabling the meticulous study of blade surfaces and the finer points of morphology, including micro-structural discrepancies indicative of serrated or smooth blade edges. For a more microscopic perspective, SEM proves invaluable, yielding minute details from the blade's surface critical for distinguishing blade types. Additionally, micro-CT, a non-destructive technique, offers a three-dimensional view of a blade's internal and external structure, helping visualize serration distribution and internal features within the blade. By combining these diverse imaging techniques, forensic experts gain a holistic and precise understanding of blade attributes, bolstering the accuracy and reliability of forensic analyses in cases involving bladed instruments [13,19,24,32–34].

For kerf marks created by knives specifically, the walls and floor of the kerf are generally even, with a V-shape cross-section at the kerf floor which may have parallel striations (Fig. 2). Most of the striation patterns of the edges are not observable by macroscopic means [17,35,36]. It is also possible to roughly estimate specific dimensions and shape of an injury-causing knife blade by examining the kerf mark, depth, distance, and stab angle. Capuani et al. [13,32] stated that epifluorescence macroscopy, optical microscopy and SEM, make it possible to distinguish between kerf marks made by serrated and smooth knives. However, excluding weapon types based on kerf mark dimensions is not recommended. Striations in kerf marks are often used as classification criteria to distinguish between weapons in research. The observable difference can be seen when examining blades with different serration points wherein the distance between the end of the kerf representing the spine of the blade and the first striation mark and the distance of all subsequent serration striations from the blade spine kerf end are used as markers corresponding to the distance between serration points on the blade and the shape of the blade itself.

Geometric examination of mark properties has been more frequently used in recent years. Barterlink et al. [17] used SEM to investigate whether kerf width could be used as the sole marker for identifying the blade type that created the mark. Although the results suggested a correlation between blade type and width of the kerf, the authors cautioned against making any specific conclusions since there is much overlap between types of weapons and blade characteristics and hence could result in false positive identifications. Thompson and Inglis [37] proposed a classification criteria for two blades while ascertaining if they could observe differences in the level of detail between imaging methods. Similar trends at each level of magnification were not expected; however, as the magnification increased, the more subtle damaged features became more apparent. Komo et al. [19], however, argued that micro-CT was the most accurate and efficient tool for identifying the details of kerf mark properties, with the advantages of being non-destructive and capable of providing precise measurements in 3D.

Given the current absence of validation studies, it is imperative to exercise caution when drawing conclusions regarding the origins of kerf marks, particularly in the context of medicolegal or criminal cases. These scenarios involve a multitude of physical variables that intricately influence kerf mark morphology, including factors such as the force and velocity of the stabbing action, as well as the unique geometrical characteristics within the bone structure.

Additionally, it must be noted that the archaeological studies examined in this context primarily focus on the analysis of cut marks present on bones, as organic tissues such as flesh and skin are typically not preserved, and hence are not directly comparable to many forensic contexts. Nevertheless, the methodologies established in experimental archaeological studies still hold significant value for forensic stab wound analysis. They not only highlight the remarkable sensitivity of cut marks to various factors but also lay the foundation for a more comprehensive understanding of changes in raw materials [38–41], tools [42,43], angles of hand movements during the mark creation [41] or even when analysing a cut mark exposed to erosion [44].

When devising experiments for the analysis of stab wounds, careful consideration should be given to the selection of imaging techniques applied, based on their broad applicability, technical proficiency, information richness, and their proven track record in prior research contexts. Such an approach fosters a conscientious and pragmatic assessment of the strengths and limitations inherent in each considered technique. While optical microscopy stands as the prevailing choice in research articles, medical CT scans take precedence in case studies. However, it is discernible that a subtle gap exists between experimental methodologies and real-world forensic cases, a disconnect that warrants attention in forthcoming investigations. The endeavour to bridge this gap calls for heightened efforts to formulate detailed, validated methodologies and to expound upon the broader implications of uniting various facets of forensic science in a synergistic manner.

When designing stab wound experiments, researchers need to define clear criteria for categorizing wounds, ensuring that similar conditions and parameters are applied across studies, and employing uniform methodologies for data collection and analysis. Such standardization not only enhances the reliability and repeatability of research outcomes but also facilitates meaningful comparisons and *meta*-analyses of findings across multiple investigations.

Moreover, in the context of forensic science, where the circumstances of crimes can vary significantly, it is vital to acknowledge and account for the diversity of individuals involved in criminal incidents. Factors such as the physical attributes of victims and assailants, their actions during the altercation, and the specific conditions of the crime scene can all exert a considerable influence on the resulting stab wounds. Therefore, a thorough understanding of these variables and their potential effects is essential for accurate and meaningful interpretation of forensic evidence [45].

Standardization plays a pivotal role in rendering the protocols employed in stab wound analysis more accessible and amenable to routinization. This, in turn, holds the potential to enhance the efficiency of investigative procedures by offering comprehensive step-by-step guidelines. Furthermore, standardization sets a foundation for streamlined future research endeavours [46].

Even with the implementation of robust experimental designs, it is essential to acknowledge the presence of numerous confounding variables and inherent random variation. These factors often pose significant challenges in the interpretation of research outcomes. However, the strategic approach of partitioning the variation within data collection into apparent components can exert a degree of control over the analytical process [47].

Certain variables, consistently underscored in the existing body of literature, can be categorized into key thematic clusters which provide a structured framework for comprehending the multifaceted variables influencing stab wound analysis. The main ones are:

Environmental and taphonomic variables: In the context of criminal forensic investigations, the analysis of bone surface modifications (BSMs) plays a crucial role in reconstructing perimortem and postmortem events. BSMs encompass various forms of trauma to bone surfaces and provide valuable insights into the circumstances surrounding deposition. These modifications, resulting from factors like thermal alteration, sharp-force trauma, scavengers, bacteria, insects, and weathering, offer information not just about weapon type, but also environmental conditions, post-mortem interval, and thermal exposure, and are often investigated by several different forensic specialists. The interplay between these environmental conditions emerges as a critical factor in understanding the formation and preservation of kerf marks and they can exert a substantial influence on the accuracy of analysis, even if fewer changes are observed in bone structures than soft tissue. Stanley et al.[23] found a significant inversely proportional linear relationship between frequency of kerf striations and accumulated degree days. They argued that optical microscopy was the best technique for consistently discriminating between striated and smooth blades regardless of the level of taphonomy to which the sample had been exposed. Other studies have highlighted the impact of decomposition on cut marks and blunt force injuries on cartilage [48] and the effect of fire on kerf marks produced by a variety of weapons including knives, cleavers and saws [49].

As environmental variables can be controlled under research conditions, well-designed experiments are vital to expand our understanding of how environmental conditions affect kerf marks [50].

Sample variables: When choosing sample material to analyse (whether that is from forensic scenarios or experimental research), it is necessary to consider whether human or animal specimens are more appropriate [18]. If the age of a kerf is known, human autopsy specimens would be most accurate and realistic to study [50]; however, there is often insufficient information available for rigorous interpretation of these sorts of samples, and there are obvious ethical issues associated with their study. Therefore, it can be argued that animal models provide more benefits since they are more wildly available, and there are also fewer regulations for using animal samples than using human ones.

Victim and assailant variables: Because of the inconsistent way wounds are acquired, caution must be exercised when attempting to classify individual kerf marks as being inflicted by a particular implement. The sequence of stabbings is complex, and these are all difficult to reproduce in an experimental context. This issue is seldom discussed in the literature. Variations in factors such as blade sharpness, the velocity of the stab, and fibre resistance all have the potential to influence the resultant mark; these variables are likely to explain why there are such vast contrasts in the conclusions between studies [18].

The numerous different interacting factors that contribute to kerf mark formation therefore results in complex systems which inherently present challenges in data interpretation. In such contexts, minimizing random error becomes a paramount objective. Moreover, discerning which variables exert the most significant influence on the outcomes assumes critical importance. This knowledge enables a strategic approach, focusing on the deliberate manipulation and comparison of specific controls to enhance research precision and clarity.

In order to establish standardized practices for stab wound analysis research and its application in medicolegal investigations, it is imperative for researchers to provide justifications for the following critical area:

- Methodology protocols: influenced by what is available (both in terms of samples and imaging facilities) as well as the relationship between the police force and the forensic analysts;
- Acquisition of mark properties: acquiring and interpreting the kerf profile requires standardised mitigations for taking the mark measurements as well as clear criteria for what should be included in the kerf description;
- Reasoning: i.e., what kerf mark features should be identified and described? This analysis of the available literature on stab wound analysis in forensic contexts has highlighted that the rationale behind the analysis is not always clear or reported, i.e. there is a general lack of justification for whether the most appropriate technique is being used to answer the question posed in a study.

The qualifications of expert witnesses in forensic fields, particularly in areas like kerf mark analysis, have come under scrutiny following recent court rulings e.g. [51]. Defining what constitutes an expert in this context lacks consensus within kerf mark analysis; while some aspects of kerf mark analysis can indeed be mastered quickly by a trained tool mark specialist, other areas remain challenging [51].

The outcomes of this study align closely with the findings outlined in Interpol's 2019 review [3], which underscored the challenges and discrepancies inherent in interpreting marks left by knives. This concurrence underscores the need for further work to assess the validity of stab wound analysis research, particularly in areas like frequency analyses, which examine how often kerf marks appear in given observations. Moreover, these reviews should explore the assignment of weighted values to different characteristics, thus serving as a compass for guiding future experimental designs. By quantifying these attributes and patterns, forensic experts can begin to establish more objective criteria for evaluating knife-related evidence. As quantitative reviews accumulate in this field, they will offer a solid foundation for constructing supporting evidence. This evidence will play a pivotal role in the ongoing development of policies within the criminal justice system, particularly in the realms of pathology and stab wound analysis. It will serve as a guide for forensic examinations, illuminating the trade-off between obtaining high-quality mark data and gathering crucial information pivotal for case resolution. By making the practice more credible in court cases, these initiatives contribute significantly to the justice system's reliability and effectiveness.

The experimental activity stemming from the application of these novel approaches holds immense forensic importance. By conducting rigorous experiments that employ advanced methodologies, researchers can enhance their ability to interpret knife-related marks accurately. This not only contributes to a deeper understanding of the physical characteristics of these marks but also enables forensic experts to provide more precise and reliable testimony in court, ultimately, impacting the criminal justice system and its capacity to ensure fair and just outcomes in cases involving stab wound analysis.

As forensic and imaging technologies rapidly evolve, opportunities to address critical limitations in stab wound analysis, ideally based on statistically significant evidence, will also arise. One approach now being harnessed for blade-wound comparison and wound track determination is 3D printing of knives [52]. This method offers a valuable means by which to identify weapons and precisely determine the direction of stabbing incidents, all without compromising trace evidence or autopsy results. Recent experiments, including ballistic gel and dynamic stabbing tests, affirm the feasibility of this method while prioritizing safety and preserving the integrity of autopsy findings [52]. This innovation represents a significant leap in forensic science, promising more accurate and efficient investigations.

Similarly, the evolution of digital imaging and immersive 3D technologies over the past decade has ushered in advanced capabilities for documenting and analysing tool mark evidence [15]. These transformative developments provide a holistic view of forensic science, spanning from research on human subjects to trace evidence analysis. High-resolution 2D and 3D imaging techniques such as laser scanning and (micro-)photogrammetry, in combination with geometric and morphometric approaches and statistical analysis, have similarly improved the capacity to discriminate between raw materials used to produce cut marks in palaeoanthropological and archaeological studies e.g. [40,43,44]. Thus, 3D imaging is clearly poised to play a central role in the future of both forensic and archaeological investigations into stab wounds and cut marks, with both disciplines able to learn from each other's research and methodologies, further enhancing their precision and impact.

This study aimed to convey and summarise current trends in stab wound analysis research, highlighting the issues and outlining potential future directions. It is worth noting that there was an insufficient number of frequency studies available in the literature that applied weighted values to individual attributes in order to ascertain their effectiveness and reliability. Consequently, kerf marks, which researchers identified as most pertinent for determining the dimensions of the blades they were examining, were documented with each characteristic carrying equal significance [34,53,54,55]. Although microscopy is the most commonly used technique in the research context (Fig. 5), discrepancies between laboratory-based experiments and case studies should be addressed in future research [3,10,11,15]. Furthermore, there is still a need to develop a thorough approach that is rigorously tested, as well as a deeper understanding of the larger implications of the research working synergistically within criminal investigations. The purpose of compiling the decision tree was to minimise these mistakes and to guide future validation studies, allowing forensic analysts to interpret their findings more efficiently, leading to conclusions with higher confidence intervals. Ultimately, this change has the potential to advance the field of stab wound analysis by enhancing the accuracy and reliability of forensic assessments, thus contributing to more effective criminal investigations and secure convictions.

5. Conclusion

Matching a kerf mark to a unique weapon or knife with absolute certainty is a challenging task, requiring both expertise and comprehensive comparative data. This challenge has been a recurring theme in stab wound analysis studies, as demonstrated in this study. To make progress in the field, it is essential to explore the reliability of the kerf mark properties used for weapon identification, and to embrace new quantitative validation studies as imaging techniques (both 2D and 3D) advance.

It is evident that there are differences among the kerf mark variants often considered helpful in identifying a weapon or weapon type. However, further research is needed to determine how frequently these marks are observed in practice. It is also intriguing to see if the frequency of these observations aligns with their actual importance in real-world forensic cases. Closing this gap between observation and practical significance will be crucial in advancing our understanding of blade edge characteristics and their role in forensic investigations. Moreover, as technology continues to advance, exploring the potential of emerging tools and methodologies for enhanced and comprehensive stab wound analysis should remain a focal point in future research efforts.

The data analytical approach that formed the basis of this study has demonstrated that cross-referencing the literature from both archaeological and forensics studies has meaningful applications, and the approach has potential to be applied to other forensic disciplines. However, it is recommended that future reviews use more sophisticated text analysis software and techniques to develop the taxonomy of these studies further.

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Linnea Bergman: Conceptualization, Formal analysis, Investigation, Writing – original draft. **Fiona Brock:** Supervision, Writing – review & editing. **David Errickson:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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