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Abstract

The analysis of toolmarks on bone and cartilage created as a result of sharp force trauma (SFT), including knife cuts, stab wounds, chop marks, and saw marks, is a specialized examination within forensic anthropology. Previous research in this area has focused on identifying tool class characteristics, but lacks reported error rates for correctly identifying these characteristics which is particularly problematic considering results may be subject to *Daubert* standards of courtroom-acceptable scientific evidence. This study produced known error rates in determining two class characteristics related to knives: blade serration (serrated, partially serrated, and non-serrated) and the side of the edge bevel of the blade (left, right, or even). Experimental cuts were made in an ideal medium (casting wax), pig cartilage, and deer bone. Three observers with varying degrees of experience examined the cuts through direct observation of the material and indirect observation (casts of the material) using two different microscopes (one with enhanced depth of field capabilities) resulting in a total of 504 observations. Serrated blades were generally distinguishable from non-serrated blades due to their distinct, patterned striations. Although the partially serrated blades were sometimes difficult to distinguish from the serrated blades, the partially serrated blades did produce distinct signature patterns that were recognized by the experienced observers. When considering serrated and partially serrated blades as one group, the overall correct classification of blade serration for the study was 96% and observer agreement was strong. Edge bevel was assessed with a reasonable degree of accuracy under optimal conditions (over 83%) but not when bone was the substrate (less than 50%) and observer agreement was moderate, suggesting further research is necessary to accurately determine edge bevel.

On average, direct versus indirect (via casts) comparison and the technological level of the microscope did not influence the results.

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EXECUTIVE SUMMARY

Description of the problem

The analysis of toolmarks on bone and cartilage created as a result of sharp force trauma (SFT) is a specialized analysis in forensic anthropology. Considering that anthropologists are experts in the analysis of hard tissues, they are often asked to examine toolmarks observed on bone and cartilage. Anthropological examination of SFT toolmarks consists of determining the tool class and does not establish toolmark uniqueness. In other words, the anthropologist is typically asked to determine the *type* of weapon used to produce a SFT defect in bone, rather than match the morphology of a defect to a specific weapon. The latter comparison falls in the scope of the forensic toolmark examiner. Over the past four years the Office of Chief Medical Examiner-New York City (OCME-NYC) has received a significant number of deaths resulting from SFT (approximately 150 cases per year). As a result of this caseload, the Forensic Anthropology Unit (FAU) within the OCME-NYC has seen an increase in requests for SFT analysis involving bone and cartilage. Currently 15 to 20% of all cases evaluated by the FAU involve SFT to bone or cartilage produced by knives. Furthermore, cases requiring expert testimony by the FAU typically involve skeletal trauma, with SFT being the majority of these cases.

Previous research has established the precedent for analyzing cut mark morphology on bone and cartilage (Andahl 1978; Bonte 1975; Symes 1992) and has promoted class characteristics. While this research has been important in establishing toolmark analysis in bone, it has largely focused on toolmarks left by saws as they are much more variable than knives and have a wider variety of class characteristics. Recent studies have evaluated the patterns produced by serrated blades (Pounder, et al. 2011; Pounder and Reeder 2011); however, additional research is necessary to establish standards of analysis and error rates for class identification for the field.

In light of the report released by National Academy of Sciences (NAS) entitled *Strengthening Forensic Science in the United States* (2009) and considering the increasing number of states adopting the *Daubert* criteria for evidentiary examination (1993), establishing quality assurance and method validation for SFT analyses in forensic anthropology is paramount. Several recent papers have advocated more earnest consideration of the *Daubert* guidelines for those conducting research and preparing testimony in forensic anthropology (Christensen 2004; Crowder and Rosella 2007; Grivas and Komar 2008; Murray and Anderson 2007). Considering this shift, forensic anthropology (as well as other forensic disciplines) must be re-conceived under the rubric of evidentiary examination and, more importantly, methods need to be based on a sound scientific foundation with justifiable protocols. Thus, research is needed to establish the scientific bases of analyses by demonstrating the validity of forensic methods. A baseline validation study is needed prior to testing method performance against additional extrinsic variables. This baseline does not exist in the anthropological literature concerning knife SFT evaluation and classification.

Purpose, Goals, and Objectives

The present research was designed to address the aforementioned problems by developing and presenting the basic concepts in knife SFT interpretation, suggesting best practices, and providing measures of reliability for evaluating SFT to bone and cartilage. The primary objective of this research design is to provide error rates for the misidentification of blade class when differentiating cut marks on bone and cartilage produced by serrated, partially serrated, and non-serrated blades. The target audiences for this research are medical examiners, coroners, toolmark examiners, and anthropologists working in the medicolegal system; however, this research has broad application and can be applied to SFT analysis in bioarchaeology and zooarchaeology. The anthropological approach to toolmark examination relies solely on class characteristics and does not attempt to individuate a suspect tool. Additional research objectives involve exploring other sources of uncertainty with the evaluation of SFT. In particular, this research evaluates if the level of technology (e.g. type of microscope) effects the examination of SFT. This was performed by comparing advanced digital microscopy equipment to the standard light microscopy equipment that is typically used in laboratories. Furthermore, this study evaluates direct and indirect toolmark analyses by comparing the results of direct microscopic analysis of the SFT defects in bone and cartilage to indirect analysis of impressions or casts of the SFT defects.

The key objectives can be summarized as:

1) Providing a baseline analysis of classifying knife SFT using experimental controls, an “ideal” medium, and a variety of knives demonstrating different serration patterns and the side of the beveled of the blade.
2) Establishing classification error rates using observers with varying degrees of experience in evaluating SFT.
3) Evaluating the use of microscope technology and determining the use of an impression (cast) of the SFT to the cartilage is an improvement over direct evaluation.
4) Presenting best practices for evaluating knife SFT in bone and cartilage to assist practitioners.

The results were presented at the 2011 American Academy of Forensic Sciences annual meeting and will be submitted for publication in the *Journal of Forensic Sciences*. Currently, no other studies have provided a baseline analysis of knife SFT to this extent in the forensic literature.

Research Design and Methods

In order to evaluate the ability to accurately determine blade class characteristics, the authors selected a diverse series of knives and produced experimental cut marks on non-human bone, non-human cartilage, and a synthetic “ideal” medium. The SFT defects produced from these experimental cuts were evaluated for class characteristics that relate to blade characteristics, including blade serration and the side of the edge bevel of the blade. The authors also examined various technological approaches to evaluate SFT to determine if this is a factor in class character identification. Finally, casts were taken of the SFT to the cartilage and the “ideal” medium to determine if evaluating the cast of a cut mark was an improvement over direct evaluation with specific reference to blade serration.

The first process in the research design was to select a series of knives that cover a range of typical blade characteristics. Fourteen different knives were purchased including serrated, partially serrated, and non-serrated blades with varied sides of edge bevel (left, right, or both). New knives were used as they provide the requisite best-case-scenario for validation studies considering that used and slightly damaged blades may contain defects that mimic serrations.

The next process was to determine the “ideal” medium in which to impact with sharp force defects. Following Petraco, Petraco and Pizzola (2005), jeweler’s wax was investigated as an “ideal” medium for examining the experimentally created toolmarks. The jeweler’s wax turned out to be too hard and brittle to effectively cut through and a medium-to-soft casting wax is presented as the preferred medium when it is necessary to transect material with an experimental cut. Wax blocks were impacted in two ways: The first impact was made by placing the cutting edge of the blade at the top of a wax block and pushing the blade down and forward, in a single motion, until the wax block was transected in half, mimicking a stab wound. Using the same knife, a second impact was made by placing the cutting edge of the blade at the top of a wax block, and moving the knife back-and-forth and down in a repetitive, reciprocating motion to mimic attempted dismemberment. The repetitive, reciprocating impact was an incomplete cut so that side of the beveled edge of the blade could be examined. In addition, the blade was kept perpendicular to the substrate so that the angle of impact would not influence the impression. The specimens were notched to record the handle-side of the blade so the direction of impact could be inferred. The two types of impacts were made for each of the 14 knives in the study sample and coded to be unknown to the analysts.

Long bones from one adult deer (*Odocoileus virginianus*) were obtained to act as proxies for human bone and porcine (*Sus scrofa*) costal cartilage was dissected from a rib cage purchased from a local butcher to act as a proxy to human cartilage. A single impact was made to the porcine cartilage, similar to the impacts made to the wax blocks as described in the above paragraph, for each of the 14 knives in the study to mimic a stab wound. The cervine long bones were also impacted in a repetitive, reciprocating motion, similar to the impacts made to the wax blocks as described in the above paragraph, by each of the 14 knives in the study to mimic attempted dismemberment. The majority of the flesh was removed from the specimens to ensure that the locations of the bone and cartilage surfaces were easily determined. The periosteum and surrounding soft tissues were left in place until the sharp force defects were made to ensure no maceration artifacts were produced on the study samples. The specimens were notched by a scalpel blade to record the handle-side of the blade so the direction of impact could be inferred. With 14 knives used in this study, 56 defects were rendered for analysis from the bone and cartilage: 14 "stab wounds" to wax + 14 "stab wounds" to cartilage + 14 "dismemberment" trauma to wax + 14 "dismemberment" trauma to bone = 56 defects. In addition, impressions were taken from the 14 wax and 14 cartilage sections with stab wound impacts, rendering an additional 28 defects for analysis. The casts were made by the authors using *AccuTrans,* a polyvinyl siloxane material. Additionally, two microscopes were utilized to test if a certain level of technology is necessary for these analyses. The first is a digital microscope manufactured by the Keyence Corporation that provides an ability to assess specimens with an increased depth of field and to reconstruct defects in three dimensions. The second is a standard light microscope that might be found in a typical laboratory setting, an Olympus SZX12. Both microscopes were assisted by external fiber optic lights to produce oblique light (axial lighting is not recommended as mentioned in the literature). Using the two different microscopes resulted in 168 analyses in the study sample for each of the three observers to analyze.

Each sample group analysis and iteration using the different microscopy equipment was performed weeks to months apart. Results were recorded so that the accuracy of the assessment of blade serration and edge bevel was determined for each researcher. Interpretations of class characteristics and overall assessment were recorded on a data collection sheet and subsequently entered into a database for analysis. Accuracy was determined through frequency values produced from classification tables. Observer agreement was assessed using Fleiss' kappa. Spearman's rank correlation coefficients were calculated to assess the consistency of results obtained from the various media and microscopes.

Results

Blade Serration

Serrated blades were generally distinguishable from non-serrated blades due to their distinct, patterned striations. Partially serrated blades were the most problematic. The signature of a partially serrated blade should exhibit both patterns of serrated and non-serrated blades as described above, but depending on the portion of the blade impacting the material, characteristics may not always be recognizable in the analysis. Because the serrated pattern was recognized, adjusted error rates were calculated by combining partially serrated and serrated blades into one group. When the adjusted error rates are considered, on average, this analysis showed an error rate of 2% in determining blade serration on both the digital and light microscopes. The level of technology does not appear to appreciably influence the result.

Like the casting wax, serrated blades were generally distinguishable from non-serrated blades in the cartilage though at slightly higher error rates. Again, partially serrated blades were the most problematic. When the adjusted error rates are considered (combining serrated and partially serrated results), on average, this analysis showed an error rate of 5% and 7% in determining blade serration on the digital and light microscopes, respectively. On average, the level of technology does not appear to influence the result.

The impressions scored slightly better, overall, than the direct observations but the difference is minimal. Again, the technology does not appear to affect the results. When partially serrated and serrated blades are combined into one group error rates are reduced for all observers.

Across the study, more than half of the partially serrated blades were misclassified as serrated blades and only one was misclassified as a non-serrated blade. When combining serrated and partially serrated blades the total percent correct of the study increases to 96%. Only seven serrated blades were classified as non-serrated and seven non-serrated blades were classified as serrated. Overall results showed a trend amongst experience level as well. After combining serrated and partially serrated blades Observer 1 had a total percent correct of 100%, Observer 2 had a total percent correct of 96%, and Observer 3 had a total percent correct of 92%. Although there is a trend seen in experience it is evident that minimal training is necessary to recognize the serrated and non-serrated signatures.

The digital scope and the standard light microscope also yielded nearly identical results. When considering serrated and partially serrated blades separately the total percent correct was 79% for the digital scope and 78% for the standard light microscope. With serration patterns combined the total percent correct was 95% for the digital microscope and 96% for the standard light microscope. Direct observations and observations of impressions yielded similar results. When considering serrated and partially serrated blades separately the total percent correct was 78% for the direct observations and 79% for observations of the impressions. With serration patterns combined the total percent correct was 96% for the direct observations and 95% for the observations of the casts.

Edge Bevel of the Blade

The side of edge bevel was assessed with varying degrees of success. Overall, the digital and standard light microscope error rates are similar within the different mediums suggesting that the increased three-dimensional capabilities of the digital microscope do not assist the observer in achieving a better accuracy in determining edge bevel. There is, however, a distinct difference when considering the bone versus the casting wax. On average, the casting wax was assessed with an error rate of less than 17% while the bone was assessed with an error rate of more than 50%. There is no obvious trend in misclassification. Each side of edge bevel misclassified as either of the other two options although blades beveled on the right side were the most easily recognizable.

Conclusions

Blade Serration

Serrated blades were generally distinguishable from non-serrated blades due to their distinct, patterned striations. While distinct striations may be considered as equidistant, it is the pattern of the striations that are important, not the distance. This is because the angle of the blade during impact is the most influential aspect of the distance between striations left by the blade. As the angle of the blade changes, the distance between the striations will change as well; however, serrated blades will still produce patterned striations, despite these changes in movement, whereas non-serrated blades will produce fine striations that are unpatterned, if visible at all. Furthermore, serrated blades may be arranged in a style in which certain teeth are set a short distance apart with a larger gap between other teeth.

Serrated blades were distinguished by all three researchers despite the width between teeth or the style of serrations. Partially serrated blades on the other hand were particularly problematic in this study for two main reasons: First, partially serrated blades have to be positioned in such a way that both the serrated and non-serrated portions of the blade impact the cutting medium (bone, cartilage, etc.). Second, the overall contact area of the cutting medium may not be large enough to fully capture the signatures from both the serrated and non-serrated portions of the partially serrated blade, making this type of blade more vulnerable to misclassification. In a forensic investigation, the analyst would not know the construction of the blade ahead of time. The authors, therefore, suggest analysts choose their wording carefully when submitting reports: an "impact with the serrated portion of a blade" may be preferable to an "impact with a serrated blade".

While the partially serrated misclassifications may be explainable, the other incorrect classifications are also particularly informative. Only two blades were responsible for six of the seven incorrect classifications of a non-serrated blade when the blade was actually serrated. Both of these blades had very coarse serrations and while distinct grooves were recognizable at widely dispersed intervals, the observers may have seen more of the fine, unpatterned striations resulting from the bevel of the blade itself. Furthermore, the shape of the serration (e.g. rounded v. pointed) may produce more subtle striations.

Only two blades were responsible for the seven incorrect classifications of a serrated blade when the blade was actually non-serrated. These two blades have characteristics of the bevel that may have resulted in the misclassification. The milling of two non-serrated blades left a regular pattern on the beveled edge that were misclassified as having been cut by a serrated blade. The numerous striations evident may lead the analyst to the conclusion that a serrated blade was used. In particular, some of the striations even appear organized in a pattern, suggesting a serrated blade. This difficult example brings up two critical points. First, the overall pattern is what is important and this is observable at low magnification and often with the naked eye. In this instance, the entire cut surface generally shows no distinct pattern of striations as would be expected. Second, it is important to examine both halves of the cut mark.

Overall, the determination of blade serration can be made with a reasonable degree of accuracy. Error rates were low and generally corresponded to the experience level of the observer suggesting additional training could further reduce error. The use of the digital or light microscope did not seem to affect the determination of blade serration nor did the observation of direct specimens compared to the observation of impressions. Although all three observers assessed edge bevel with a reasonable degree of accuracy under optimal conditions, assessing edge bevel from bone appears to be problematic. Additional research into the characteristics presented here and further use of the three-dimensional capabilities of the digital microscope may reduce this error in the future.

Implications for Policy and Practice

While not all states have adopted the *Daubert* standard, research has shown that in both *Frye* and *Daubert* jurisdictions, 94% of state court judges contend that they find *Daubert* valuable to their decision-making (Moreno 2003). The interpretation of sharp force defects resulting from knives is not a rare occurrence in the postmortem examination. On average, approximately 18% of homicides investigated per year by the New York City's Office of Chief Medical Examiner involved SFT (2009). Previous research has documented the potential for knives to produce characteristics in bone and cartilage that may assist in identifying the type of weapon used to create the sharp force defect. This research provided empirical validation testing for the classification of blade serration and edge bevel of the blade that can assist the analyst in the laboratory and the courtroom. Through the features described here and the exploration of different analytical equipment and indirect toolmark examination on impressions made from the defect, the analyst is provided with benchmark results for determining class characteristics as a result of SFT.

1 INTRODUCTION

Forensic anthropologists are often asked to examine defects on bone and cartilage created as a result of sharp force trauma (SFT) including knife cuts, stab wounds, chop marks, and saw marks. SFT can involve a variety of weapons and tools, and any tool with a sharp edge can produce sharp force defects. In most cases, the weapon is unknown and the anthropologist is called upon to give a general description of the weapon, if possible. Accordingly, the anthropological approach to these cases investigates *class characteristics* and does not attempt to individuate a suspect tool. Previous research has established the precedent for analyzing cut mark morphology on bone and cartilage (Andahl 1978; Bonte 1975; Symes 1992) and has promoted class characteristics in the analysis of SFT defects on bone and cartilage. While this research has been invaluable in advancing toolmark analysis in bone, it has largely focused on toolmarks left by saws as they are much more variable than knives and thus have the capability to leave more class characteristics (such as blade width, set, tooth shape, teeth per inch, blade power, etc.). Recent studies have evaluated the patterns produced by serrated blades (Pounder, et al. 2011; Pounder and Reeder 2011); however, additional research is necessary to establish standards of analysis and error rates for class identification for the field.

Anthropologists are increasingly involved in toolmark examination in forensic investigations. Over the past four years the Office of Chief Medical Examiner-New York City (OCME-NYC) has documented a significant number of deaths resulting from SFT (approximately 150 cases per year). Statistics have shown that approximately 18% of homicides in New York City are the result of sharp force injuries (2009). As a result of this caseload, the Forensic Anthropology Unit (FAU) within the OCME-NYC has seen an increase in requests for SFT analyses involving bone and cartilage. Currently 15 to 20% of all cases evaluated by the

FAU involve SFT to bone or cartilage produced by knives. Furthermore, cases requiring expert testimony by the FAU typically involve skeletal trauma, with SFT being the majority of these cases. In a retrospective study on 58 fatalities due to stab or incised wounds from the Department of Pathology and Forensic Medicine in Garches, France, 53% of the cases showed SFT defects to bone or cartilage (Banasr, et al. 2003) suggesting that the anthropologist may have an important role in these types of cases. Despite the increasing frequency of sharp force injuries in the medicolegal setting, descriptions and discussion of SFT in the anthropological literature are found mostly in the paleoanthropological or bioarchaeological literature. These studies review the accuracy of cut mark recognition in bone with a focus on differentiating scavenging or systematic butchery activities of early hominins and humans from carnivore tooth marks (Bromage and Boyde 1984; Walker and Long 1978). For the most part, these studies lack the necessary information to provide viable input for the medicolegal setting.

In the 1970's, Bonte (1975) and Andahl (1978) introduced the topic of sharp force toolmark analysis of bone in the forensic context. Bonte (1975) conducted the first research to closely examine toolmark striations from saws and serrated knives in human bone, and concluded that, in reference to serrated knives, each knife type resulted in characteristic patterns. Andahl (1978) described numerous saw cut characteristics in metal and animal bone. While these analyses introduced toolmark analysis as a valid pursuit in the examination of bone, the characteristics described by these authors focus largely on saw mark analysis and are often oversimplified. It was not until Symes' (1992) dissertation involving knife and saw mark analysis that effective characteristics in examining SFT in bone were fully realized. Symes' methodology is based on his evaluation of the diagnostic potential of several features of saw marks on bones, the ability of these features to indicate saw dimensions, and the potential of these characteristics to discriminate between different classes of saws and knives. Symes (1992) emphasizes that an anthropological examination of bone can reveal class characteristics, not individualizing characteristics; however, Symes' initial research only considered serrated blades and did not provide the analyst with information to differentiate serrated and non-serrated blades on bone and cartilage.

Symes' research culminated in the 2005 National Institute of Justice grant (Grant 2005-IJ-CX-K016) entitled "Knife and Saw Toolmark Analysis in Bone", which set the standard for the analysis of SFT on bone. This research investigated and validated class characteristics as a mechanism for identifying tools used in SFT cases. While this research has been invaluable in advancing toolmark analysis in bone, it largely focused on toolmarks left by saws. This is likely because saws typically impact more bone than knives given that saws are generally used in an attempt to completely transect bone (i.e. dismemberment) whereas knives associated with stab wounds or joint disarticulations leave fewer marks in the bone and cartilage for examination. The preference for researchers to investigate saws rather than knives, and to validate the analysis of SFT from saws, has resulted in a deficiency in reported error rates for classifying class characteristics.

While a handful of articles exist involving the analysis of knife cut marks (Ernest 1991; Mikko and Hornsby 1995; Rao and Hart 1983), chop marks tend to receive more focus than stab injuries in the anthropological literature (Alunni-Perret, et al. 2005; Humphrey and Hutchinson 2001; Tucker, et al. 2001). Despite these deficiencies, continued research by Symes and colleagues (Symes, et al. 1998; Symes, et al. 2002; Symes, et al. 2007) has helped to lay the foundation from which further efforts can be made to provide standards and reliable methods for the analysis of both saw and knife marks on bone.

Validation studies, though desperately needed, are often problematic owing to the tendency of researchers to modify or adapt the techniques rather than test the methods as originally presented. This has been the case in anthropological studies evaluating the ability to accurately identify SFT toolmark characteristics in bone. Rather than evaluate the baseline examination of cut mark characteristics on pristine bone, researchers often investigate the effect that taphonomic conditions (i.e., burned or buried remains) have on the ability to identify class characteristics (de Gruchy and Rogers 2002; Marciniak 2009). Evaluating class characteristics on bone that has undergone taphonomic changes will not allow for the researcher to determine the degree of error inherent to the method. A baseline validation study, as presented in this research, is needed prior to testing method performance against additional extrinsic variables. In other forensic disciplines practitioners often rely on a collection of published validation studies for the technique(s) used.

The deficiency in reported error rates is problematic considering results may be subject to *Daubert* (1993) or *Frye* (1923) standards of courtroom-acceptable scientific evidence or similar rules of evidence as determined by the state courts. In *Ramirez v. State of Florida* (2001), the Florida Supreme Court ruled that the evidence presented by the toolmark examiner, who determined that the knife presented for analysis was the specific knife used in a homicide, did not demonstrate the requirements of scientific acceptance and reliability. While this case is concerning for those that evaluate toolmarks, the examiner was attempting to identify unique characteristics not class characteristics. Regardless, current anthropological SFT studies lack attention to method validation, error rates, and professional standards which is further concerning in light of the recent National Academy of Sciences (NAS) report entitled *Strengthening Forensic Science in the United States* (Committee on Identifying the Needs of the Forensic

Sciences Community; Committee on Applied and Theoretical Statistics), in which attention was given to the lack of scientific testing and error rates in certain disciplines within the forensic sciences.

Concern over evidentiary examination has resulted in recent studies evaluating the efficiency of knife SFT on bone and cartilage. One recent study determined that there is no correlation between serrations on the blade and the regularity of striation patterns in experimentally cut pig cartilage (Love, et al. 2010), while research by Pounder and colleagues (Pounder, et al. 2011; Pounder and Reeder 2011) suggests otherwise. In light of the disagreements between researchers and the need for error rates and standards in knife SFT analysis, this research was designed to evaluate the ability to accurately associate a knife toolmark with a particular blade class. Using an experimental model, SFT defects were produced and evaluated for class characteristics that relate to two blade characteristics: blade serration (serrated, partially serrated, and non-serrated) and the side of beveled edge of the blade (left, right, or both). The goals of this research are to produce error rates, suggest best practices for knife SFT evaluation, and demonstrate the overall utility of the technique.

2 MATERIALS AND METHODS

In order to evaluate the ability to accurately determine blade class characteristics, the authors selected a series of knives that represent various characteristics and produced experimental SFT on non-human bone, non-human cartilage, and a synthetic “ideal” medium. The SFT defects were evaluated for class characteristics that relate blade characteristics including blade serration and the side of the beveled edge of the blade. The authors also evaluated different microscopy equipment to evaluate SFT to determine if this is a factor in class character identification. Finally, casts were taken of the SFT to the cartilage and the "ideal" medium to determine if evaluating the cast of a cut mark was an improvement over direct evaluation.

Knives Utilized

Before describing the particular knives utilized it is important to show the anatomy of the knife (Figure 1) and discuss how the class characteristics are produced. The spine of the blade refers to the back of the blade, which is the unsharpened, thick portion that supports the entire blade. The edge bevel (or grind) is the thinned, cutting surface of the blade. A serrated blade is produced by removing scallops of metal from the beveled edge. Serrated blades are expected to leave striations representing the scallops or teeth on the cutting surface of the blade and should show a distinct pattern (Figure 2). Non-serrated blades are expected to either leave no visible striations or fine, unpatterned striations that represent the milling (grinding) of the beveled edge of the blade (Figure 3). Because the serrated blades contain are scalloped or contain "teeth", serrated blades can typically be distinguished from non-serrated blades by the distinct, patterned striations left behind. Partially serrated blades are expected to show a combination of patterned and unpatterned striations. In other words, you may expect to find signatures of blades that are serrated, non-serrated, or both. Figure 1 is a diagram of a partially serrated blade with a non-serrated edge or grind toward the tip end, and a serrated or scalloped area toward the blade handle. A signature pattern example created by a partially serrated blade is shown in Figure 4. In this study, a blade was pre-determined to be serrated, non-serrated, or partially serrated based on the portion of the blade that was intended to impact the different mediums. Appendix A provides pictures of the 14 blades used in this study and the portion of the blade that was used.

The side of the beveled edge of the blade is expected to be visible in an incomplete cut. Edge bevel can either be left, right, or both as noted in Table 1. When the beveled edge is oriented down, if the milled edge of the blade is visible when the blade is oriented to the left of the handle, then the blade has a left edge bevel (as seen in Figure 1). When the beveled edge is oriented down, if the milled edge of the blade is visible when the blade is oriented to the right of the handle then the blade has a right edge bevel. Blades may also have edge bevels on both sides. In profile, the longer, more angled kerf wall would represent the side of edge bevel assuming the direction of cutting stroke is known (Figure 5).

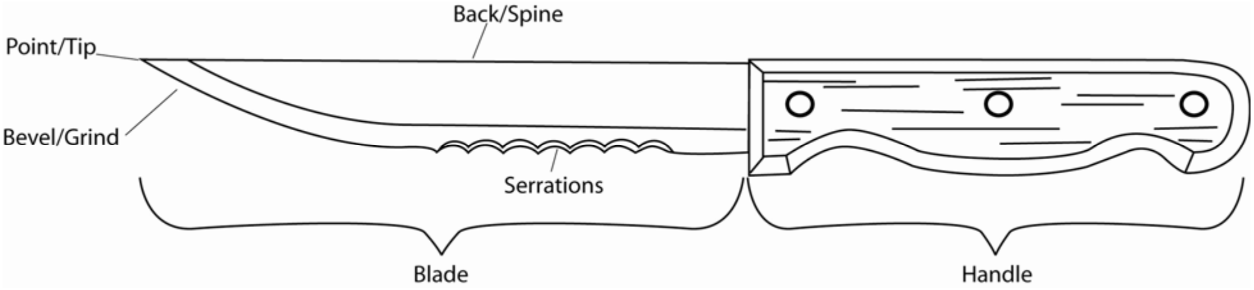

Figure 1. Diagram showing knife terminology relevant to this study.

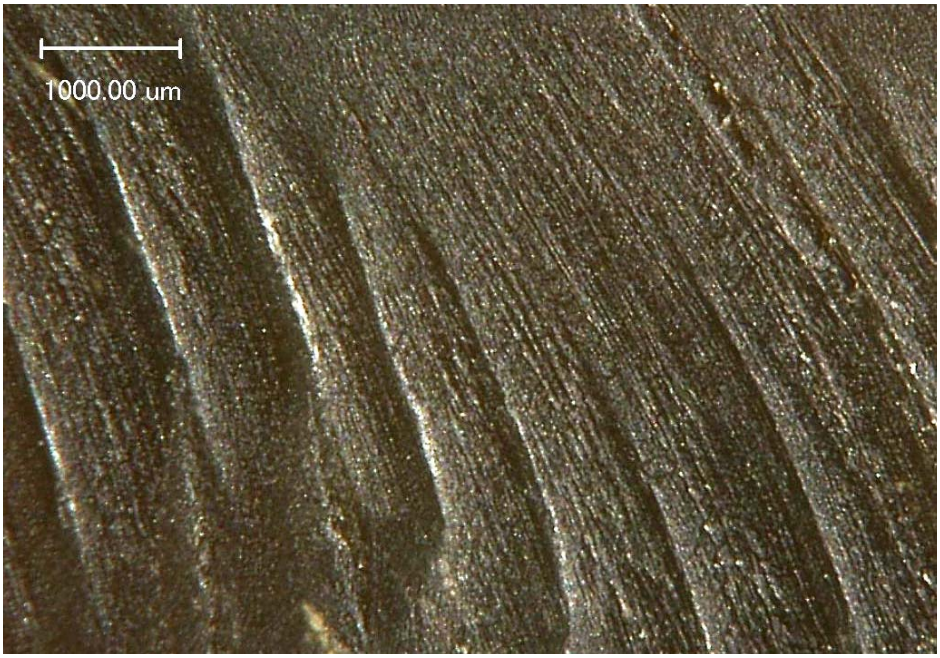

Figure 2. 30x image of patterned striations indicative of a serrated blade.

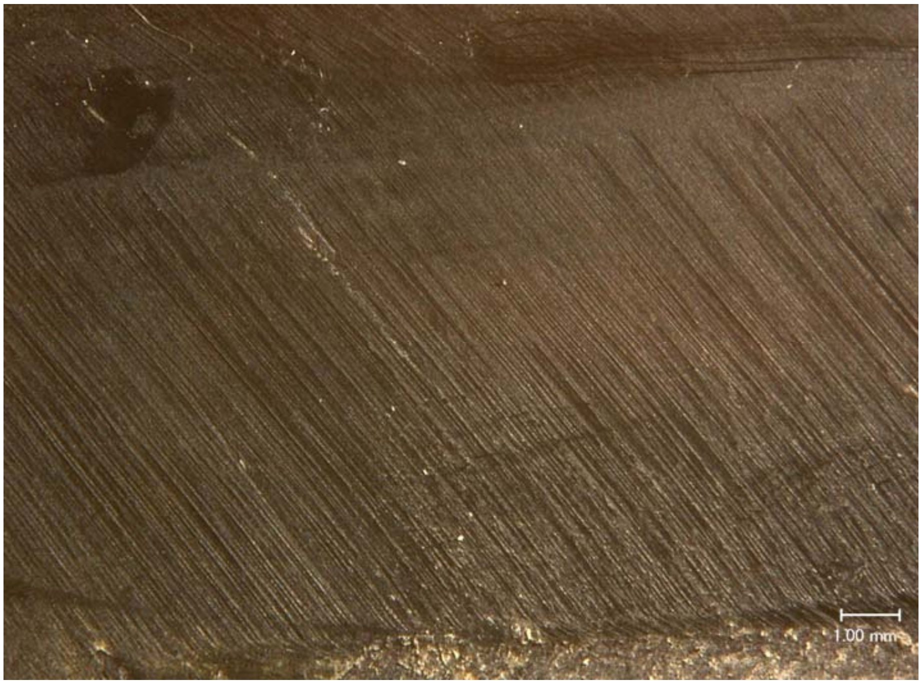

Figure 3. 20x image of a fine, unpatterned striations indicative of a non-serrated blade.

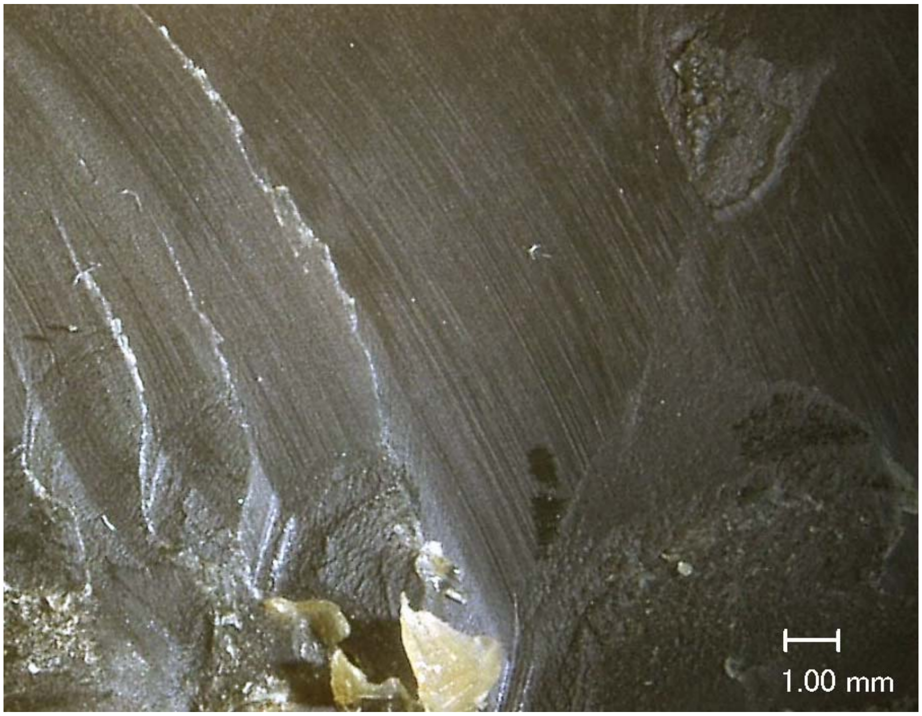

Figure 4. 10x image shows both coarse, patterned striations and fine, unpatterned striations.

Figure 5. 20x image showing kerf shape indicating a left edge bevel.

Fourteen different knives were purchased and utilized to allow the investigators to evaluate the range of class characteristics reported in the literature. This includes serrated, partially serrated, and non-serrated blades with varied sides of edge bevel (left, right, or both). Knives with varying teeth per inch and serration styles were evaluated to increase the range of class characteristics in the study. New knives were purchased considering that older or used knives may contain defects that mimic characteristics or distort characteristics. Table 1 provides a summary of the knives used in the study. Appendix A shows images of each knife. It is also important to note that authors were deliberate in making the experimental cuts so that expected class of serration might be represented in the material. For instance, Blades 3 and 4 have relatively small portions of the blade that are non-serrated. The experimental impacts deliberately included contact with this part of the blade and these blades were considered partially serrated. Also, Blade 14 exhibits a distinct serrated pattern near the handle but all impacts were made only with the non-serrated portion of the blade and, accordingly, the blade is considered non-serrated for this study.

Table 1. Knives utilized in the study.

Code	Blade	Serrations	Bevel	Notes
1	"Jim Wagner Reality Based" Tactical Folder	Partial	Left	Teeth set apart at different intervals
2	Myerchin Offshore Crew Knife w/ Marlin Spike	Partial	Left	Teeth set apart at different intervals
3	Miracle Blade III Slicer	Partial	Both	Teeth set apart at different intervals
4	Myerchin Offshore Safety/Dive Knife	Partial	Right	Teeth set apart at different intervals
5	Oneida Steak Knife	Serrated	Left	Coarse serrations
6	Sunbeam Steak Knife	Serrated	Left	Fine serrations, Major/Minor pattern of serrations
7	Miracle Blade III Steak Knife	Serrated	Both	Very coarse serrations
8	Miracle Blade III Filet Knife	Serrated	Right	Very coarse serrations
9	Carving Knife Blank	Serrated	Right	Very coarse serrations
10	Spyderco Byrd Meadowlark Steel Plain Edge Folder	Non-Serrated	Both	
11	Paula Dean Paring Knife	Non-Serrated	None	Not sharpened
12	Miracle Blade III Paring Knife	Non-Serrated	Right	
13	Gerber Plain Edge Folder w/ Gut Hook	Non-Serrated	Both	Heavy duty
14	Böker Plus Bowie Knife	Non-Serrated	Left	

Producing Sharp Force Defects

Every blade was used to make cuts on bone, cartilage, and casting wax. Although bone and cartilage are the focus of this research project, the researchers felt it was necessary first to determine if the blade class characteristics could be accurately assessed under "ideal" circumstances. Following Petraco, Petraco and Pizzola (2005), jeweler's wax was investigated as an "ideal" medium for examining the experimentally created toolmarks. Despite the results of their research, it was determined that the jeweler's wax was too hard and brittle to effectively cut through the material. After investigating several different options, a medium-to-soft casting wax was chosen as the preferred material when it was necessary to transect material with an experimental cut.

Samples of deer bone (*Odocoileus virginianus*) were obtained to act as proxies for human bone. Typically, pig (*Sus scrofa*) is used in anthropological studies; however, available pig remains are typically juvenile. Juvenile pig bone contains large amounts of fibrolamellar or plexiform bone, which may not be the ideal model considering that human bone consists of Haversian or osteonal bone. As an alternative, long bones from one adult deer were acquired for the study sample. Porcine costal cartilage was dissected from a rib cage purchased from a local butcher to act as a proxy to human cartilage.

Wax blocks were impacted in two ways: in a single impact transecting the wax block (to mimic a stab wound) and in a repetitive, reciprocating motion (to mimic attempted dismemberment). Stab wounds were mimicked by a single impact by placing the cutting edge of the knife at the top of the wax block and pushing the blade down and forward, transecting the block into two halves. Dismemberment SFT was mimicked by placing the cutting edge of the knife at the top of the wax block and moving the blade back-and-forth and down, creating a kerf. The repetitive, reciprocating impact was an incomplete cut so that the side of the edge bevel of the blade. In addition, the blade was kept perpendicular to the substrate so that the angle of impact would not influence the impression.

The rib cage was separated into individual pieces so focused impacts could be made on individual cartilages, but the surrounding soft tissues were left intact. The porcine cartilage was impacted in a single impact transecting the cartilage mimicking a stab wound in the same manner as the wax blocks. Once impacted, each specimen was trimmed and placed in a 10% formalin solution to fix the cartilage and to keep it from decomposing. The trimmed edges were notched to differentiate the trimmed surface from the cut mark to be evaluated. For the deer long bones, the majority of the flesh was removed from the specimens to ensure that the locations of the bone surfaces were easily determined. The periosteum and surrounding soft tissues were left in place until the sharp force defects were produced to ensure no defleshing artifacts were produced on the study samples. The deer long bones were then impacted in a repetitive, reciprocating motion to mimic attempted dismemberment in the same manner as the wax blocks. The specimens were notched on one end to record the direction of impact. After producing the sharp force defects on the remains, the bones were macerated in hot water with *Tergazyme*. *Tergazyme* is an enzymatic detergent that gently breaks down and removes muscle tissue, requiring less manipulation by the researcher, and ensuring that no additional toolmarks were made as a result of processing. With 14 knives used in this study, 56 defects were rendered for analysis from the bone and cartilage.

In addition, analysts may be required to conduct analyses in which the evidentiary material cannot be removed from its primary location and is prohibitive to fit under a microscope. In such circumstances, high-quality impressions or casts are a viable alternative. Accordingly, impressions were taken from the wax and cartilage rendering an additional 28 defects for analysis. The casts were made by the authors using *AccuTrans,* a polyvinyl siloxane material.

Cut Mark Examination

An individual not associated with the project coded the five sample groups (wax, cartilage, bone, impressions of wax, and impressions of cartilage) differently to ensure a blind analysis was performed. Each sample group analysis and iteration was performed weeks to months apart. Additionally, two microscopes were utilized to test if a certain level of technology is necessary for these analyses. The first is a digital microscope manufactured by the Keyence Corporation that provides an ability to assess specimens with an increased depth of field and to reconstruct defects in three dimensions. The second is a standard light microscope that might be found in a typical laboratory setting, an Olympus SZX12. Both microscopes were assisted by external fiber optic lights to produce oblique light (axial lighting is not recommended). Using the two different microscopes resulted in 168 analyses in the study sample. Three researchers, with varying degrees of experience analyzing SFT, assessed the sample group cut marks. Observer 1 (CWR) has been trained extensively and has conducted previous research in anthropological SFT analyses; Observer 2 (CMC) has limited sharp force training but extensive experience in microscopy; and Observer 3 (JSF) has limited experience in SFT analyses and microscopy. Minimal training was conducted prior to analyses with the main focus being to clarify terminology. With 168 analyses performed by each observer, there were a total of 504 analyses performed in this study.

Results were recorded so that the accuracy of the assessment of blade serration and bevel was determined for each researcher. Accuracy was determined through frequency values produced from classification tables. Interpretations of class characteristics and overall assessment were recorded on a data collection sheet (Appendix B) and subsequently entered into a database for analysis. Each sheet included information on the type of microscope used (light vs. digital) and the sample examined (bone, cartilage, ideal medium, etc.). The kerf wall observations included whether striations were visible, and if so, whether those striations were patterned. Striations visible on the kerf wall were recorded as *fine* (microscopic striations), *coarse* (thick striations, especially when compared to finer striations, often visible with the naked eye), a combination of fine and coarse striations, or *none* (no striations visible). If striations were observed, the striations were recorded as *patterned* (regularly spaced striations), *unpatterned* (irregularly spaced or haphazard striations), or a combination of both. If the blade serration could not be evaluated for any reason, it was recorded as indeterminate (indeterminate assessments were not included in the results).

The kerf shape (v-shaped cut mark produced by the cutting instrument) created on the baseline samples (medium-to-soft wax models) and bone samples, was also recorded on the data collection sheet. The kerf shape was recorded as either *right hypotenuse* (the right arm of the “v” leans more toward the right side), *left hypotenuse* (the left arm of the “v” leans more toward the left side), *isosceles* (the arms of the “v” are equidistant from each other), or *other.* If *kerf floor tracks* (multiple scratches on the floor of the cut mark) or *edge deformation/lipping* (damage to the edges of the sample) was observed on a sample during analysis, these features were recorded on the data collection sheet as “other characteristics”. The final conclusions on blade characteristics were made by each analyst for each sample and were recorded at the end of the data collection sheet. Patterned striations were determined to be serrated blades, non-patterned striations were determined to be non-serrated blades, and a mixture of patterned and non-patterned striations were determined to be partially serrated blades. If the striations or striation pattern could not be evaluated for any reason, it was recorded as indeterminate. A right hypotenuse was determined to be a blade with an edge bevel on the right side, a left hypotenuse was determined to be a blade with an edge bevel on the left side, and an isosceles triangle was determined to be blade with an edge bevel on the both sides. If the kerf shape could not be evaluated for any reason, it was recorded as indeterminate (indeterminate assessments were not included in the results).

Fleiss’ kappa was calculated using the irr 0.83 package in R 2.12.1 to assess inter-observer error. Fleiss’ kappa is appropriate for categorical error and measures the agreement between observers (Fleiss 1971). It can roughly be considered as a ratio of observed versus expected values where the measure of observer agreement and is expressed as a value between 0 and 1. Although the interpretation of kappa statistics has been debated (Feinstein and Cicchetti 1990; Maclure and Willet 1987), then benchmarks for strength of agreement provided by Landis and Koch (1977) are used for this study. Spearman's rank correlation coefficients (rs) were also calculated using R 2.12.1 to evaluate the consistency of results obtained from the various media and microscopes.

3 RESULTS

Blade Serration

Error rates for assessments of blade serration using the casting wax are shown in Table 2. Serrated blades were generally distinguishable from non-serrated blades owing to their distinct, patterned striations. Partially serrated blades were the most problematic. Two researchers misclassified two of the four partially serrated blades as serrated blades while the third researcher misclassified all four as serrated blades. The signature of a partially serrated blade should exhibit both patterns of serrated and non-serrated blades as described above, but depending on the portion of the blade impacting the material, characteristics may not always be recognizable in the analysis. This distinction will be revisited but because the serrated pattern was recognized, adjusted error rates are presented in the casting wax when partially serrated and serrated blades are combined into one group (Table 3). When the adjusted error rates are considered, on average, this analysis showed an error rate of 2% in determining blade serration on both the digital and light microscopes. The level of technology does not appear to appreciably influence the result.

Error rates for assessments of blade serration using the cartilage are shown in Table 4. Like the casting wax, serrated blades were generally distinguishable from non-serrated blades though at slightly higher error rates. Again, partially serrated blades were the most problematic. Adjusted error rates are presented in the cartilage when partially serrated and serrated blades are combined into one group (Table 5). When the adjusted error rates are considered, on average, this analysis showed an error rate of 5% and 7% in determining blade serration on the digital and light microscopes, respectively. On average, the level of technology does not appear to influence the result.

Table 2. Raw error rates in "ideal" medium for serration.

	Digital Microscope	Light Microscope
Observer 1	0.14	0.14
Observer 2	0.14	0.14
Observer 3	0.29	0.31
Average	0.19	0.20

Table 3. Error rates without the serrated/partially serrated distinction in "ideal" medium.

	Digital Microscope	Light Microscope
Observer 1	0.00	0.00
Observer 2	0.00	0.00
Observer 3	0.07	0.07
Average	0.02	0.02

Table 4. Raw error rates in cartilage for serration.

	Digital Microscope	Light Microscope
Observer 1	0.14	0.14
Observer 2	0.29	0.21
Observer 3	0.29	0.43
Average	0.24	0.26

Table 5. Error rates without the serrated/partially serrated distinction in cartilage.

	Digital Microscope	Light Microscope
Observer 1	0.00	0.00
Observer 2	0.07	0.00
Observer 3	0.07	0.21
Average	0.05	0.07

Error rates for assessments of blade serration from impressions of the casting wax are shown in Table 6. The impressions scored slightly better, overall, than the direct observations but the difference is minimal. Again, the technology does not appear to affect the results. When partially serrated and serrated blades are combined into one group error rates fell to zero for all observers (Table 7). Error rates for assessments of blade serration from impressions of the cartilage are shown in Table 8. The impression error rates are nearly identical to the direct observations. Again, the technology does not appear to affect the overall results. When partially serrated and serrated blades are combined into one group, error rates are reduced for all observers (Table 9).

Table 6. Raw error rates in impressions of "ideal" medium for serration.

	Digital Microscope	Light Microscope
Observer 1	0.14	0.14
Observer 2	0.14	0.14
Observer 3	0.21	0.14
Average	0.17	0.14

Table 7. Error rates without the serrated/partially serrated distinction in impressions of "ideal" medium

	Digital Microscope	Light Microscope
Observer 1	0.00	0.00
Observer 2	0.00	0.00
Observer 3	0.00	0.00
Average	0.00	0.00

Table 8. Raw error rates in impressions of cartilage for serration.

	Digital Microscope	Light Microscope
Observer 1	0.14	0.21
Observer 2	0.29	0.29
Observer 3	0.36	0.21
Average	0.26	0.24

Table 9. Error rates without the serrated/partially serrated distinction in cartilage.

	Digital Microscope	Light Microscope
Observer 1	0.00	0.00
Observer 2	0.14	0.14
Observer 3	0.21	0.07
Average	0.12	0.07

The combined results for the entire study are shown in Tables 10 and 11. Table 10 retains the distinction between serrated and partially serrated blades. Across the study, more than half of the partially serrated blades were misclassified as serrated blades and only one was misclassified as a non-serrated blade. When combining serrated and partially serrated blades the total percent correct of the study increases to 96% (Table 11). Only seven serrated blades were classified as non-serrated and seven non-serrated blades were classified as serrated. Overall results showed a trend amongst experience level as well. After combining serrated and partially serrated blades Observer 1 had a total percent correct of 100%, Observer 2 had a total percent correct of 96%, and Observer 3 had a total percent correct of 92%. Although there is a trend seen in experience it is evident that minimal training is necessary to recognize the serrated and non-serrated signatures. The results of Fleiss' kappa test for inter-observer agreement were considered strong when partially serrated blades were considered as their own category (*k* = 0.77) and when partially serrated and serrated blades were condensed into one category (*k* = 0.854).

Table 10. The classification matrix for the entire study with all observers, mediums, and technology combined.

	Classified Into				
Group	Total	Serrated	Partially Serrated	Non-Serrated	Percent Correct
Serrated	120	108	6	6	90%
Partially Serrated	96	52	43	1	45%
Non-Serrated	119	7	0	102	94%
				Total Correct: 263 out of 335	79%

Table 11. The classification matrix without the serrated/partially serrated distinction for the entire study with all observers, mediums, and technology combined.

	Classified Into			
Group	Total	Serrated Combined	Non-Serrated	Percent Correct
Serrated Combined	216	210	7	97%
Non-Serrated	119	7	111	93%
			Total Correct: 321 out of 335	96%

The digital scope and the standard light microscope also yielded nearly identical results. When considering serrated and partially serrated blades separately the total percent correct was 79% for the digital scope and 78% for the standard light microscope. With serration patterns combined the total percent correct was 95% for the digital microscope and 96% for the standard light microscope. Spearman's rank correlation coefficients were statistically significant: r = 0.883 (p-value = <0.0001) when considering serrated and partially serrated blades separately and r = 0.896 (p-value = <0.0001) when considering serrated and partially serrated blades together. This further suggests that the increased depth of field provided by the digital microscope is not necessary to effectively determine blade serration.

Direct observations and observations of impressions also yielded similar results. When considering serrated and partially serrated blades separately, the total percent correct was 78% for the direct observations scope and 79% for observations of the impressions. With serration patterns combined, the total percent correct was 96% for the direct observations and 95% for the observations of the casts. When comparing the results for the casting wax versus the *Accutrans* molds, the Spearman's rank correlation coefficients were statistically significant: r = 0.953 (p-value = <0.0001) when considering serrated and partially serrated blades separately and r = 0.974 (p-value = <0.0001) when considering serrated and partially serrated blades together. The results were slightly worse (but still statistically significant) when comparing the results for the cartilage versus the *Accutrans* molds. The Spearman's rank correlation coefficients were: r = 0.703 (p-value = <0.0001) when considering serrated and partially serrated blades separately and r = 0.745 (p-value = <0.0001) when considering serrated and partially serrated blades together. Though the results were less consistent there was no trend noted as the amount of incorrect observations were nearly identical between the cartilage and the *Accutrans*.

Edge Bevel of the Blade

The side of the edge bevel of the blade was assessed with varying degrees of success. Error rates for assessments of edge bevel in the casting wax are shown in Table 12. The error rates for assessments of edge bevel in bone are shown in Table 13. Overall, the digital and standard light microscope error rates are similar within the different mediums suggesting that the increased three-dimensional capabilities of the digital microscope do not assist the observer in achieving a better accuracy in determining edge bevel. There is, however, a distinct difference when considering the bone versus the casting wax. On average, the casting wax was assessed with an error rate of less than 17% while the bone was assessed with an error rate of more than 50%. Table 14 shows the classification matrix of the combined bone and wax results. There is no obvious trend in misclassification. Each side of edge bevel misclassified as either of the other two options. Edges beveled on the right side were determined correctly most often.

Table 12. Error rates in ideal medium for edge bevel.

	Digital Microscope	Light Microscope
Observer 1	0.14	0.07
Observer 2	0.09	0.17
Observer 3	0.29	0.21
Average	0.17	0.15

Table 13. Error rates in bone for edge bevel.

	Digital Microscope	Light Microscope
Observer 1	0.57	0.64
Observer 2	0.50	0.57
Observer 3	0.36	0.43
Average	0.50	0.55

Table 14. The classification matrix for determining edge bevel for the entire study with all observers, mediums, and technology combined.

	Classified Into				
Group	Total	Left	Right	Even	Percent Correct
Left	57	34	12	11	60%
Right	47	4	41	2	87%
Even	59	17	11	31	53%
	Total Correct: 108 out of 163				65%

The results of Fleiss' kappa test for inter-observer agreement in assessing edge bevel is considered moderate ($k = 0.543$). Although, the observations from the wax were classified correctly more often the level of technology did not seem to make a difference. Spearman's rank correlation coefficients were significant (r = 0.553, p-value = 1.23e-7) when comparing the results from the light and digital microscopes.

4 CONCLUSIONS

4.1 Discussion

Blade Serration

Serrated blades were generally distinguishable from non-serrated blades due to their distinct, patterned striations. While distinct striations may be considered as equidistant, it is the pattern of the striations that are important, not the distance. The angle of the impact of the blade is the most influential aspect of the distance between striations left by blade teeth. Furthermore, serrated blades may be arranged in a style in which certain teeth are set a short distance apart with a larger gap between other teeth (Figure 6). As the blade moves, the angle of the blade will change, and as a result, the distance between the striations will also change. Serrated blades, however, will still produce patterned striations, despite these changes in movement, whereas non-serrated blades will produce fine striations that are unpatterned, if visible at all. Serrated blades were distinguished by all three researchers despite the width between teeth or the style of serrations.

Partially serrated blades were particularly problematic in this study. This is a factor of the portion of the blade impacting the material as well as the overall contact area. If only the serrated aspect of a partially serrated blade impacts the material then the resulting signature would appear serrated. In a forensic investigation, the analyst would not know the construction of the blade ahead of time. The authors, therefore, suggest analysts choose their wording carefully when submitting reports: an “impact with the serrated portion of a blade” may be preferable to an “impact with a serrated blade”. There could also be a discrepancy as to when a blade would be considered partially serrated. For instance, Blades 3 and 4 (see Appendix A) in the study were defined as partially serrated but there is only a short portion of the blade that is non-serrated before the serrated portion. On the other hand, even though Blade 14 (see Appendix A) has both serrated and non-serrated blade characteristics and thus could be considered a partially serrated blade, only the non-serrated portion of this knife was used to impact the three different mediums (bone, cartilage, and wax) and thus was classified as non-serrated in this study.

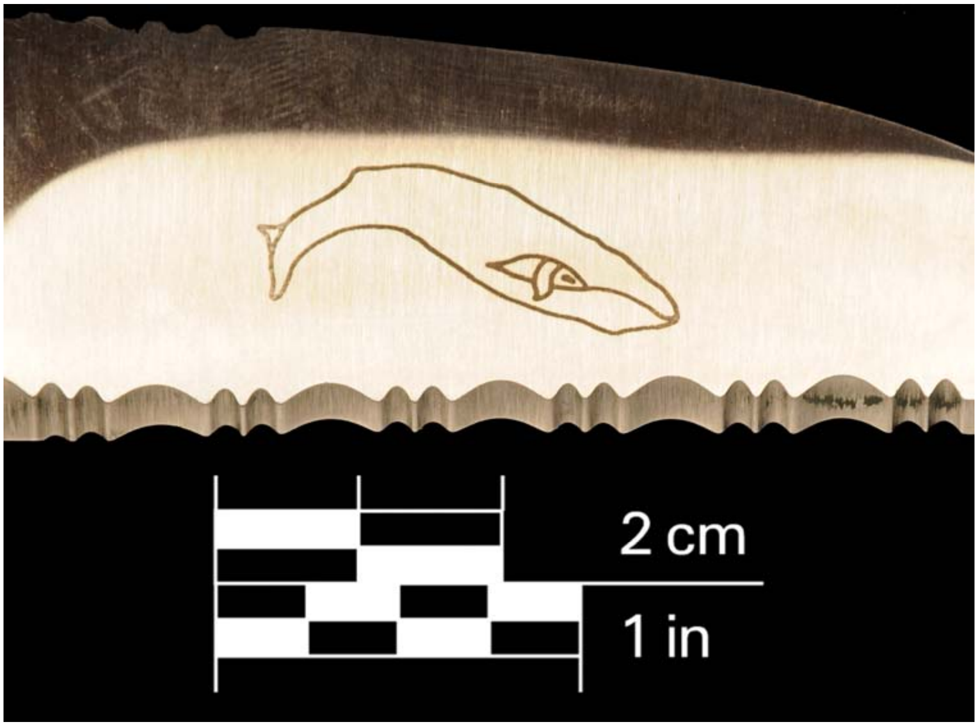

Figure 6. Exemplar knife showing a pattern of serrations where the distance between teeth varies.

While the partially serrated misclassifications may be explainable, the other incorrect classifications are also particularly informative. Only two blades were responsible for six of the seven incorrect classifications of a non-serrated blade when the blade was actually serrated. Both of these blades had very coarse serrations and while distinct grooves were recognizable at widely dispersed intervals, the observers may have seen more of the fine, unpatterned striations resulting from the bevel of the blade itself (Figure 7). Figure 8 shows a cut cartilage from one of the serrated blades that was incorrectly classified as a non-serrated cut. With the serrations being so far apart there is less potential for striations to be left on the material. In addition, the rounded, scalloped appearance of the serrations may not leave the same marks as typically pointed, sharp teeth of serrated blades.

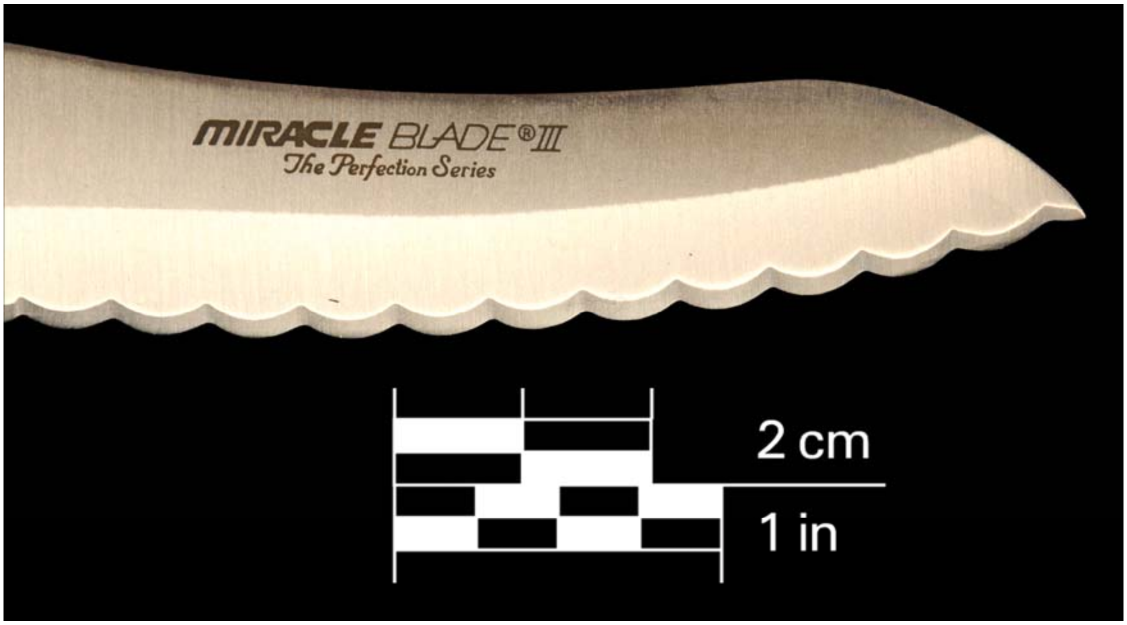

Figure 7. View of the blade serration style that led to the incorrect classifications as non-serrated.

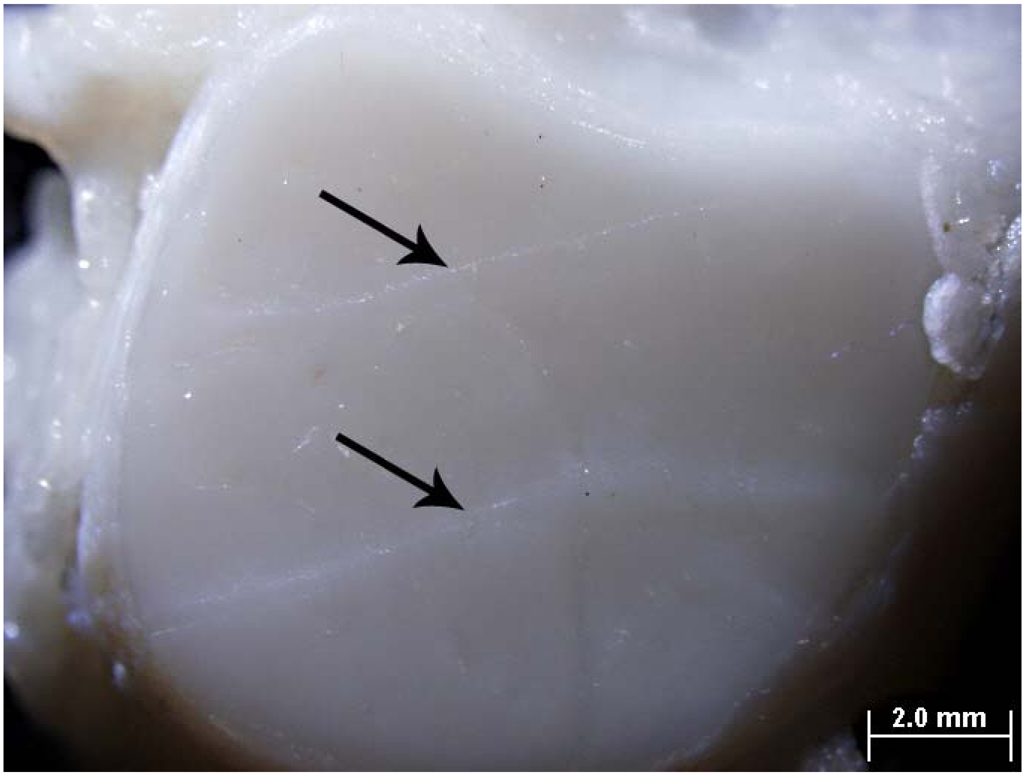

Figure 8. View (12.5x) of a cartilage cut by a serrated blade that was incorrectly classified as a non-serrated blade. Note the faint, widely dispersed striations.

Only two blades were responsible for the seven incorrect classifications of a serrated blade when the blade was actually non-serrated. These two blades have characteristics of the bevel that may have resulted in the misclassification. The milling of the blade left a regular pattern on the beveled edge (Figure 9). Figure 10 shows a cast of a cartilage that was misclassified as having been cut with the non-serrated blade shown in Figure 9. The numerous striations evident may lead the analyst to the conclusion that a serrated blade was used. In particular, some of the striations even appear organized in a pattern. Figure 10 is taken at 20x magnification and one can imagine that higher magnification, particularly on the left side of the image, may suggest a serrated pattern. This difficult example brings up two important points. First, the overall pattern is what is important and this is observable at low magnification and often with the naked eye. In this instance, the entire cut surface generally shows no distinct pattern of striations as would be expected (See Figure 2). Second, it is important to examine both halves of the cut mark. Figure 11 shows the cast of the opposite kerf wall of the same cut as shown in Figure 10 which would less likely to be confused as a serrated cut.

Figure 9. The surface of one of the non-serrated blades misclassified as a serrated blade. Note the distinct pattern left by the milling of the beveled edge.

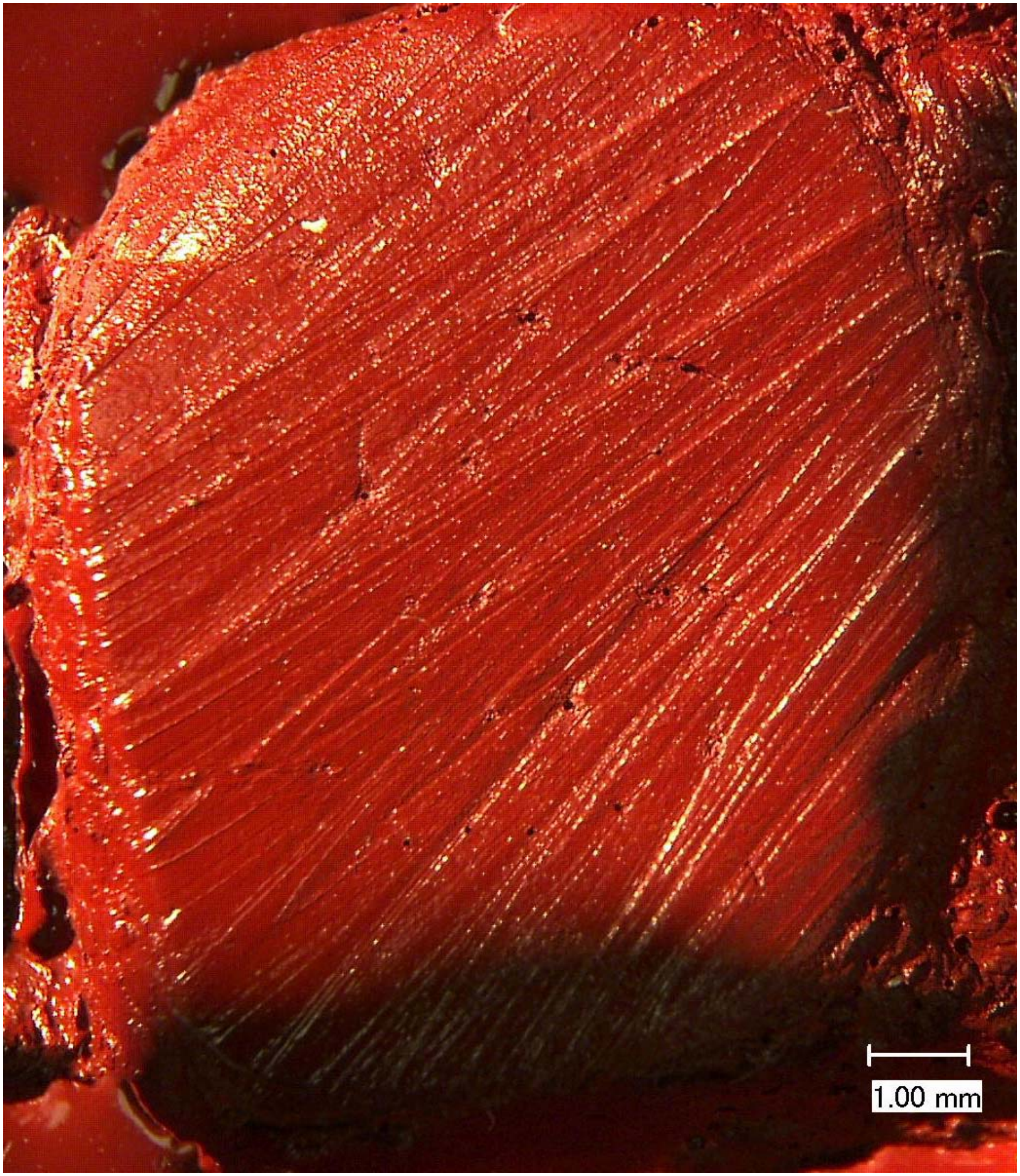

Figure 10. View **(**20x) of the cast of a cartilage cut by a non-serrated blade. Due to the more distinct striations than a typical non-serrated blade and the fact the same appear to be patterned, this was one of the misclassified blades in the study.

Figure 11. View (20x) of the opposite kerf wall shown in Figure 9. It is important to examine both kerf walls.

Edge Bevel of the Blade

The determination of edge bevel was not consistently accurate although bevel was much more easily distinguished in the casting wax than the bone. One possibility for this is the construction of the wax blocks. The blocks were rectangular and the cuts were made on a flat surface and the resulting kerf may have been more easily read from the block rather than the rounded, irregular bone. No noticeable differences were found between the digital microscope and the standard light microscope. The digital light microscope, however, has the capability to render three-dimensional images which may, with refinement, become useful in determining edge bevel. Figure 12 shows a screenshot of the three-dimensional profile reconstruction provided by the *Keyence* digital microscope. The observers were not able to consistently interpret the edge bevel using this technology but feel that there is potential for future applications.

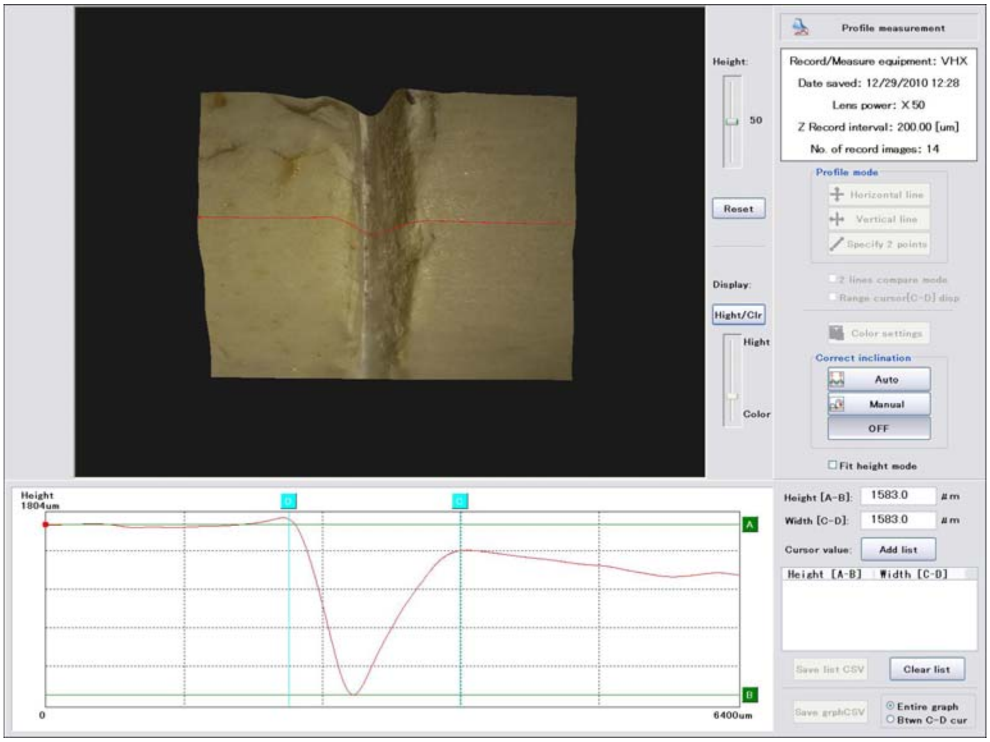

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Figure 12. A screenshot of the three-dimensional reconstruction provided by the digital Keyence microscope at 50x. Note the profile at the bottom showing the longer right kerf wall.

In addition, several criteria were noted in relatively low frequencies but are presented here as they may assist future researchers attempting to distinguish the side of edge bevel. The research design was set up so that the observers would know what side of the bone the individual would be cutting the bone. In other words, it was known which side the handle of the blade would be in relation to the cut material. In a forensic investigation this may not be known but during the analyses some criteria were noted that would assist the investigator. Occasionally, a "trailing scratch" was noted on the side of the bone the cutting individual was standing, or the handle-side of the cut (Figure 13). This is a superficial groove and was likely the result of a pass of the blade falling out of the kerf and was always noted handle-side of the cut.

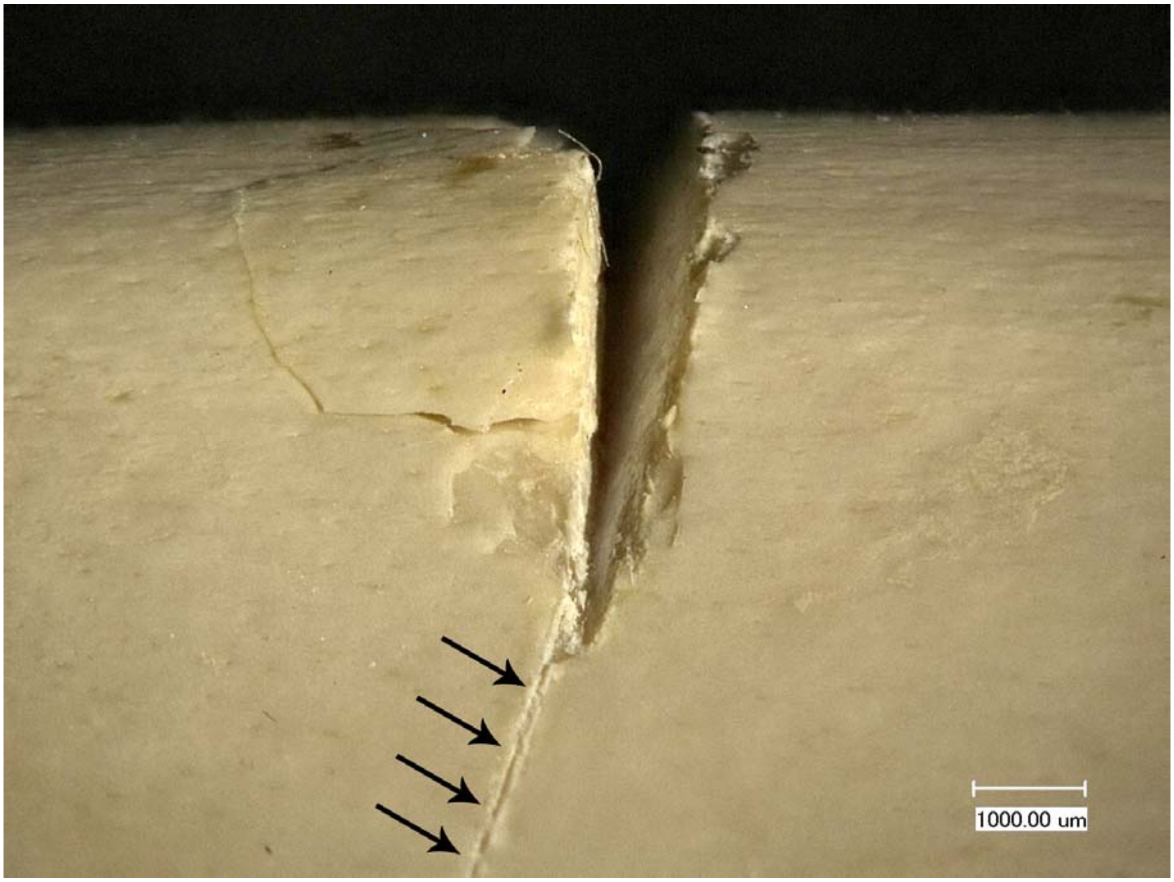

Figure 13. View (30x) of a kerf. The arrows show the "trailing scratch" indicating the side of the bone the individual cutting the bone was standing.

Several bones also exhibit kerf margin deformation where a build-up of ragged, deformed bone appears along the kerf margin (Figure 14). In serrated blades, this feature was noted on the side of the kerf that corresponded to the side of the edge bevel of the blade. In non-serrated blades, kerf margin deformation was noted but was not consistently associated with the side of edge bevel. In most cases, the amount of deformation seen in serrated blades was greater than that seen in non-serrated blades.

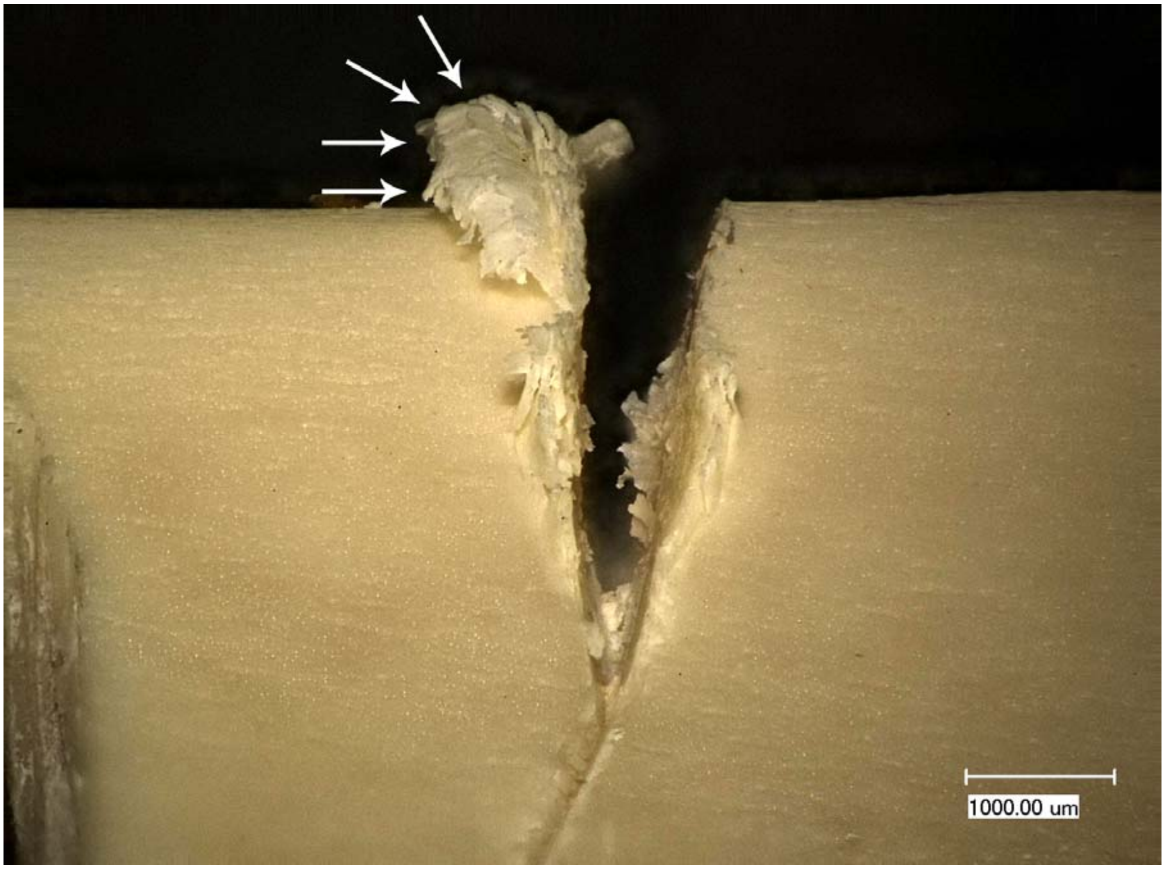

Figure 14. View (40x) of a kerf showing kerf margin deformation, highlighted by the arrows.

Conclusions

The determination of blade serration can be made with a reasonable degree of accuracy. Error rates were low and generally corresponded to the experience level of the observer suggesting additional training could further reduce error. The use of the digital or light microscope did not seem to affect the determination of blade serration nor did the observation of direct specimens compared to the observation of impressions. In addition to recognizing coarse, patterned striations from fine, unpatterned striations, we suggest that analysts assess blade serration using angled light, low level magnification, and by examining both sides of the kerf. Although all three observers assessed edge bevel with a reasonable degree of accuracy under optimal conditions, assessing edge bevel from bone appears to be problematic. Additional research into the characteristics presented here and further use of the three-dimensional capabilities of the digital microscope may reduce this error in the future.

4.2 Implications for Policy and Practice

While not all states have adopted the *Daubert* standard, research has shown that in both *Frye* and *Daubert* jurisdictions, 94% of state court judges contend that they find *Daubert* valuable to their decision-making (Moreno 2003). Considering how law and science continue to converge, the science of anthropology (as well as other forensic disciplines) should be conceived under the rubric of evidentiary examination and methods need to be based on a sound scientific foundation with justifiable protocols. The interpretation of sharp force defects resulting from knives is not a rare occurrence in the postmortem examination. On average, approximately 18% of homicides investigated per year by the New York City's Office of Chief Medical Examiner involved SFT (2009). Previous research has documented the potential for knives to produce characteristics in bone and cartilage that may assist in identifying the type of weapon used to create the sharp force defect. This research provided empirical validation testing for the classification of blade serration and edge bevel that can assist the analyst in the laboratory and the courtroom. Through the features described here and the exploration of different analytical equipment and indirect toolmark examination on impressions made from the defect, the analyst is provided a benchmark for determining class characteristics as a result of SFT.

4.3 Implications for further research

Blade Serration

This study showed that serrated blades and non-serrated blades left different signatures that could be identified reliably by observers with varying degrees of experience. Following this experimental research, future research can focus on reducing the error rate produced in this study. Additionally, probabilistic models may be created to incorporate confidence of features noted, surface area impacted, repetition of pattern, etc., to further statistical basis for blade serration determination.

Edge Bevel of the Blade

The study showed a difficulty in assessing edge bevel. The features noted in the discussion, however, may provide a basis for future research into determining edge bevel. In comparison to blade serration, edge bevel has received little attention in literature. Edge bevel is a distinct feature of a suspected tool, a recordable class characteristic, and a potentially useful addition to toolmark analyses. It is hoped that future research may utilize some of the features proposed above and may be used to refine techniques in order to identify this characteristic.

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6 DISSEMINATION OF RESEARCH FINDINGS

Preliminary results were presented, by invitation, to the National Institute of Justice Impression and Pattern Evidence Symposium:

Rainwater, C.W., C.M. Crowder, and J.S. Fridie
2010 Microscopic analysis of sharp force trauma from knives: Preliminary results of a validation study. Presented at the National Institute of Justice Impression and Pattern Evidence Symposium, Clearwater Beach, FL, August 2-5.

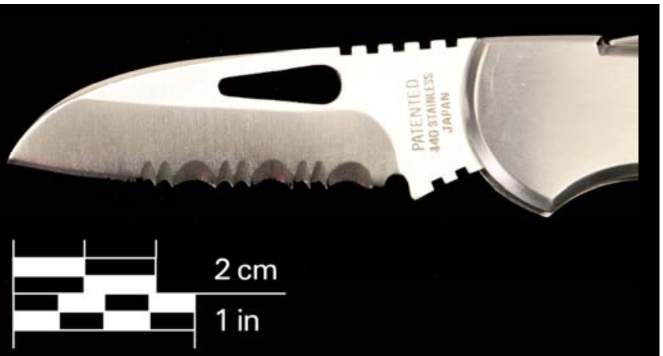
Additionally, the final results of the project were presented at the 2011 Annual Meeting of the American Academy of Forensic Sciences (AAFS):

Rainwater, C.W., C.M. Crowder, and J.S. Fridie
2011 Microscopic analysis of sharp force trauma from knives: A validation study. Presented at the 63rd Annual Meeting of the American Academy of Forensic Sciences, Chicago IL, February 21-26.

Following the final grant report, the research will be submitted for publication in the *Journal of Forensic Sciences.* The results will also be presented to the Scientific Working Group for Forensic Anthropology or SWGANTH. This working group consists of professionals from the forensic anthropology community with the goal to identify and recommend "best practice" within the forensic anthropology discipline. The SWGANTH has created committees, which are populated by U.S. and international forensic anthropologists, to examine targeted issues for the purpose of identifying what is best practice for the profession to follow. One of the committees covers trauma analysis, which includes SFT interpretation. Currently, the guidelines submitted by the trauma committee have not been finalized.

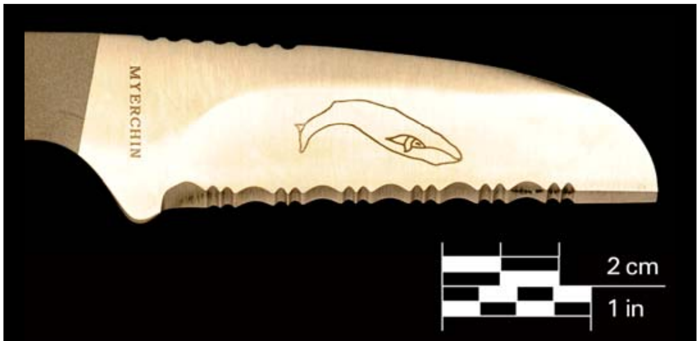
APPENDIX A. The knives utilized in the study.

Blade #1: Jim Wagner "Reality Based Blade"

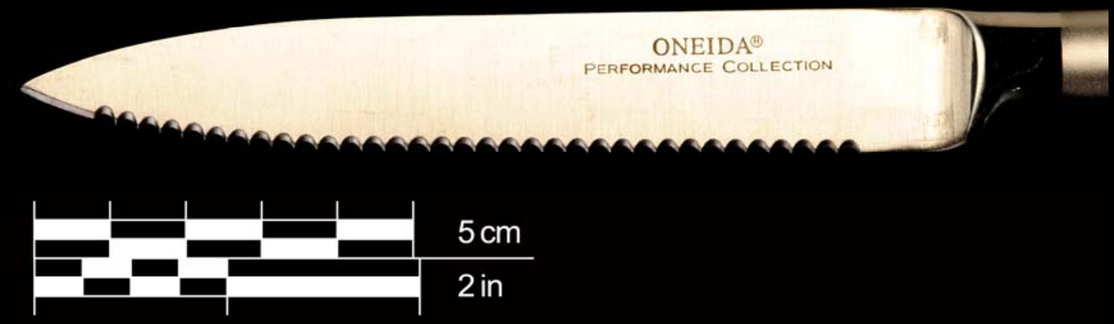


Blade #2: Myerchin Offshore Crew Knife w/ Marlin Spike

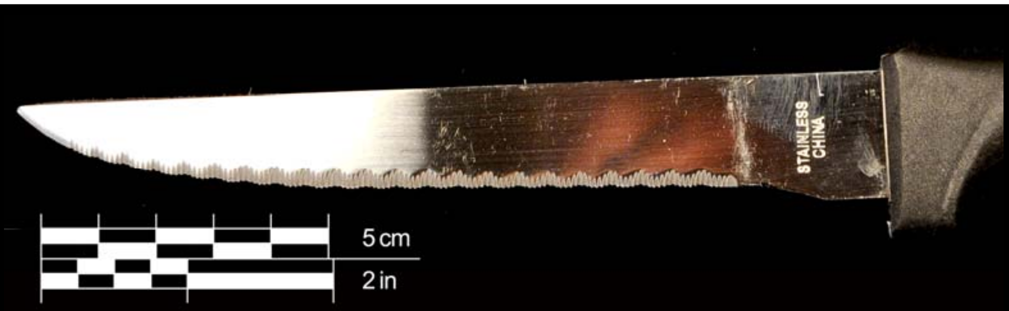
Blade #3: Miracle Blade III Slicer



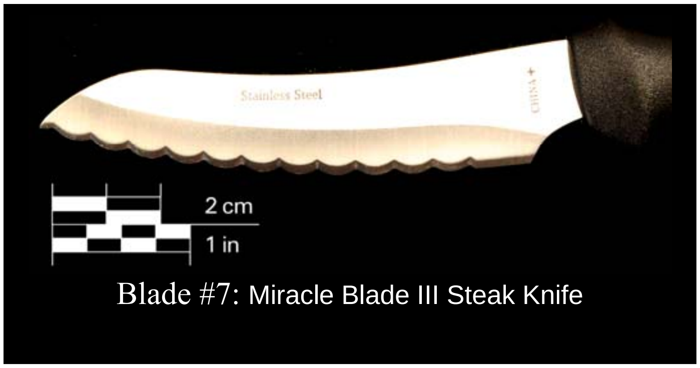
Blade #4: Myerchin Offshore Safety/Dive Knife



Blade #5: Oneida Steak Knife

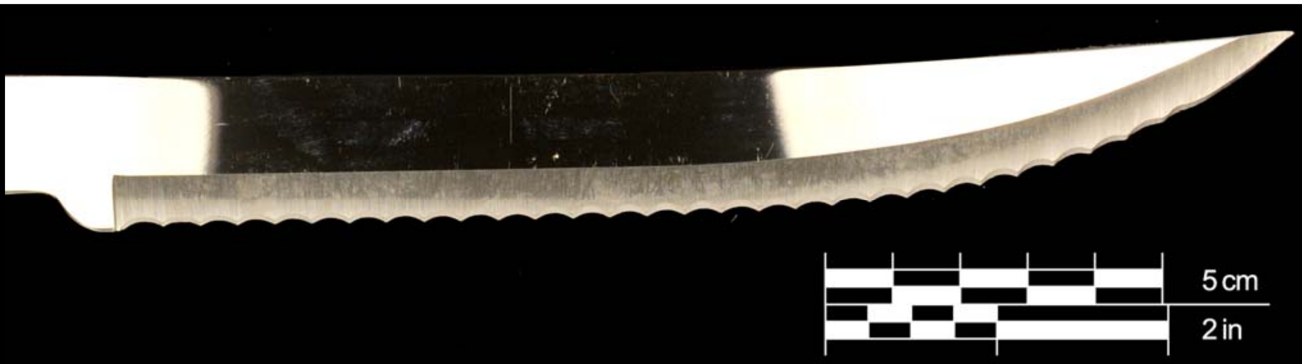


Blade #6: Sunbeam Steak Knife



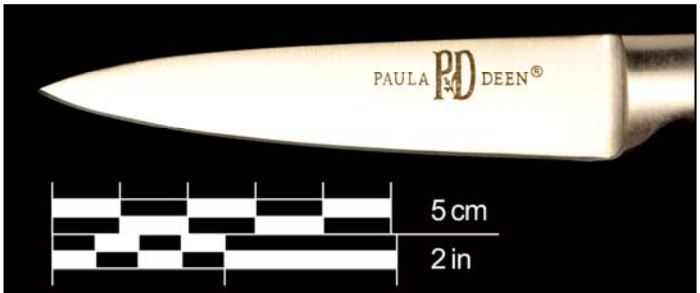
Blade #7: Miracle Blade III Steak Knife

Blade #8: Miracle Blade III Filet Knife

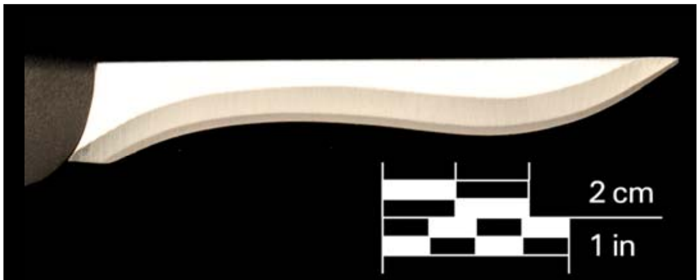


Blade #9: Carving Knife Blank

Blade #10: Spyderco Byrd Meadowlark Steel Plain Edge Folder

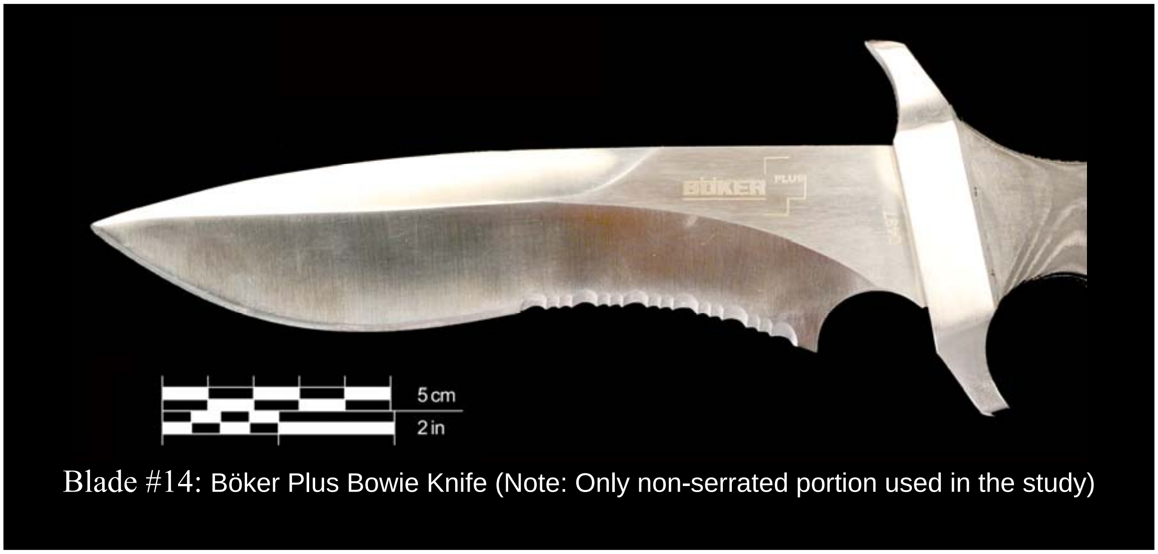


Blade #11: Paula Dean Paring Knife



Blade #12: Miracle Blade III Paring Knife

Blade #13: Gerber Plain Edge Folder w/ Gut Hook



Blade #14: Böker Plus Bowie Knife (Note: Only non-serrated portion used in the study)

APPENDIX B. Data collection sheet

Kerf Wall

Left - Diagram

☐ Fine striations
☐ Coarse striations
☐ Fine/coarse striations
☐ None

☐ Patterned
☐ Unpatterned
☐ Both

Right - Diagram

☐ Fine striations
☐ Coarse striations
☐ Fine/coarse striations
☐ None

☐ Patterned
☐ Unpatterned
☐ Both

Notes:

Kerf Shape

Diagram

☐ Hypotenuse right
☐ Isosceles
☐ Hypotenuse left
☐ Other (See Notes)

Notes:

Other Characteristics

Additional Description:

☐ Kerf Floor Tracks
☐ Edge deformation/lipping

Conclusions

☐ Serrated ☐ Partially Serrated ☐ Non-serrated ☐ Indeterminate

☐ Left Bevel ☐ Right Bevel ☐ Even Bevel ☐ Indeterminate