Document Title:	**Independent Validation Test of Microscopic Saw Mark Analysis**
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Document No.:	**241745**
Date Received:	**April 2013**
Award Number:	**2010-DN-BX-K235**

National Institute of Justice
Award No. 2010-DN-BX-K235

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Abstract

Microscopic saw mark analysis is a well published, generally accepted, and commonly used method. The strength of the method is that it is based on easily recognized qualitative and quantitative characteristics of a saw mark using standard laboratory equipment. Despite the method's attractiveness, it has not been independently validated, nor has the potential error rate been defined. Federal guidelines regarding admissibility of forensic testimony have become more rigorous in recent years, requiring a defined potential error rate. As a result, microscopic saw mark analysis fails to meet the requirements set forth by the *Federal Rules of Evidence*.

The presented study is an independent validation test of microscopic saw mark analysis. The method, as published, was replicated without deviation and an ample sample size was generated for statistically sound analysis. Four morphologically different saws were used to make 58 partial and 58 complete saw marks in human femurs. The saw marks were examined independently by three doctoral level anthropologists using a digital microscope. Fifteen variables were documented for each saw mark. Descriptive analysis was performed using the Microsoft Excel 2007 statistical package. The data were further analyzed with classification trees and random forest classifiers grown with the "rpart" and "randomForest" libraries of the open source data analysis package R. Four variables were used in the classification tree and random forest classifier analyses: wall shape; floor shape; minimum kerf width; and average tooth hop.

Several of the variables were shown to be replicable and informative in the classification of saw type, but other variables were rarely observed. Minimum kerf width and average tooth hop were two variables that showed little variation between the three analysts; however, average tooth hop was identified on only 71% of the specimens. The two random forest classifier analyses returned an out-of-bag error rate of 8.62% and 17.82%, respectively. As stated above, these analyses included average tooth hop, meaning nearly 30% of the data points were missing. The missing data were adaptively imputed using the random forest program, but this strategy weakens the results.

The greatest value of the study is the presentation of a statistically sound approach to evaluating the reliability and accuracy of a class characteristic recognition method and should serve as a model for testing similar methods. The classification tree analysis generates a process to optimally combine the variables to derive a decision rule or estimation procedure for new cases. The random forest classifier analysis defines the error rate associated with the method.

This study fulfilled the goal of defining the error rate associated with microscopic saw mark analysis for the chosen saw types; however, the number of saws used in this study limits the application of the results. In order to strengthen the method, validation studies on a larger scale must be done. The authors of this study recommend using the classification tree and the random forest classifier analyses in future studies.

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Executive Summary

Problem

Microscopic saw mark analysis is a class characteristic recognition method that is generally accepted by the forensic science community as evident in the publications of the method and associated research in peer-reviewed journals. The publications were focused on first establishing the method and then improving it through identifying more features of a saw mark using more advanced microscopes. However, independent validation studies of the method are lacking in the literature as well as a defined error rate inherent to the method. These insufficiencies limit the application of the method to forensic evidence. Without independent testing and a defined error rate, forensic evidence derived from the method does not meet the requirements for admissibility set forth by the *Federal Rules of Evidence*. (1975; 2000)

Purpose, Objective, Goal

The purpose of the study is to bring microscopic saw mark analysis in compliance with the requirements for evidence admissibility set forth by the *Federal Rules of Evidence* (1975, 2000). The objective of the study is to independently test microscopic saw mark analysis of test marks in bone using variables as described by Symes and colleagues (Symes 1992; Symes et al. 2010) in a manner that enables statistically sound evaluation of the results. The goal of the study is to quantify the uncertainty in the conclusions drawn from microscope saw mark examination, defining the limits of reliability and the accuracy that the method can achieve.

Research Design

Test saw marks were made in bone and analyzed using a Keyence VHX-1000 Digital Light Microscope with 5 – 50x lens (Osaka, Japan). Four morphologically different saws were chosen for the study: 8 teeth per inch (TPI) crosscut saw; 18 TPI wavy set hacksaw; 18 TPI raker set hacksaw; and 10 TPI raker set reciprocating saw. Four anatomical gifted human femurs were used in the study. The femurs were previously frozen and some muscle remained adhered to the bone. Prior to the study, each femur was thawed in a refrigeration unit. Each saw was assigned to one of the four femurs and only one saw was used on each bone. Fifteen test marks were made with each saw, except for the reciprocating saw in which only 13 test marks were made. Each test mark (specimen) consisted of a false start and complete cut. The false starts were made with five consecutive power strokes. The reciprocating saw is an electrically powered saw and the number of power stokes could not be accurately counted. For consistency, the sawyer attempted to make the reciprocating saw false starts equal in depth to the false starts made with the manually powered saws. The test marks were separated from each other using a surgical saw. The surgical saw cut surfaces were scored to insure they were not mistaken as test cut surfaces.

Each test mark was randomly assigned a specimen number from 1-58. Each test mark was processed in a water soap bath at 70C for 24 hours. The soap used was Superkleen (Delta Foremost; Memphis, TN) and the concentration was approximately 1/3 soap to 2/3 water. The first test mark cut into each femur was at the level of the lesser trochanter. The muscle adhered to the bone required these specimens to be processed for an additional 24 hours.

The digital microscope and a dual-arm fiber-optic light source (Schott; Auburn, NY) were used to evaluate the features of the test marks. The measuring function of the Keyence software was used to measure the quantitative variables. The microscope was calibrated each day prior to analyzing the specimens. The indirect light generated by the optic light box and the high density resolution function of the Keyence software were used to enhance the features of the test mark.

Fifteen variables were evaluated in each test mark; the variables were defined following Symes (1992) and Symes et al. (2010). An abbreviated list of variables and their definitions is provided in Table 1. The wall that abutted the false start was analyzed. Each specimen was examined independently by three doctoral level forensic anthropologists.

TABLE 1 – List of Variables Recorded and Abbreviated Descriptions*

Variable	Description
Minimum Kerf Width	Minimum distance across the false start
Kerf Wall Shape	Description of the false start wall alignment when viewed in the normal plane
Trough Morphology	Shape of the floor of the kerf when viewed in the normal plane
Tooth Width	Dimensions of the tooth grooves observed on the kerf floor
Trough Width	Width of the trough at the kerf floor
Floor Dips	Distance between peaks observed on the kerf floor (false start or break-away spur)

Kerf Floor Shape	Shape of the kerf floor when viewed perpendicular to the normal plane
Pullout Striations	Distance between scratches that run perpendicular to the striations on the kerf wall
Consistency of Cut	Number of directional changes of the striations across the kerf wall
Tooth Hop	Distance between peaks in the striations observed in the kerf wall
Harmonics	Distance between peaks observed three-dimensionally in the kerf wall
Break-away Spur	Spur of bone at the endpoint of a complete saw cut
Kerf Flare	Flaring of the false start at one end
Entrance Shavings	Polishing of the margins of the kerf wall
Exit Chipping	Small divots in the margins of the kerf wall

*The first 11 variables listed reflect class characteristics of the saw mark; the last four reflect the progression and direction of the saw through the bone.

Descriptive analysis was performed using the Microsoft Excel 2007 statistical package. The data were further analyzed using classification trees and random forest classifier grown with the “rpart” and “randomForest” libraries of the open-source data analysis package R (www.r-project.org). All data obtained from all the analysts were included in the statistical analyses. Two classification trees were developed. The first classification tree was grown using the variables floor shape, wall shape, minimum kerf width and average tooth hop. The second classification tree was grown using the variables wall shape, minimum kerf width and average tooth hop. Using the same sets of variables, two random forest classifiers were generated to identify the out-of-bag (OOB) estimate of error rate and variable importance.

Results

The study design resulted in 58 specimens. The statistical analyses of the data show several variables to be replicable and informative in the classification of saw type. Minimum kerf width was highly consistent between the three analysts. The kerf floor shape was another informative variable when coded as W-shaped. Perfect agreement was obtained between the crosscut saw and a W-shaped floor by all three analysts. In contrast, there was virtually no association of the floor shape (rounded or flat) and the saw type (raker set hacksaw, wavy set hacksaw, and raker set reciprocating saw). Tooth hop was recognized by all three analysts on 41 (71%) of the cut surfaces. Plotting of average tooth hop measurement showed little variation between the three analysts.

Several of the variables were too infrequently observed to be statistically evaluated: trough morphology; kerf flare; pullout striation; entrance shavings; and harmonics. A trough floor other than flat was recorded by one analyst once. Kerf flare was identified in only 18 (10%) of the specimens by the three analysts. Pullout striations were observed by all three analysts in only 3 (5%) of the specimens. Entrance shavings and harmonics were not identified by all three analysts in any of the saw marks.

The classification tree grown on the variables floor shape, wall shape, minimum kerf width and average tooth hop demonstrated that floor shape and minimum kerf width were informative variables in saw classification. The classification tree grown on wall shape, minimum kerf width, and average tooth hop showed that minimum kerf width was the most informative variable in saw classification. Two random forest classifiers were performed. The first classification tree was grown using the variables: wall shape, minimum kerf width, floor shape and average tooth hop. The second classification tree was grown removing the variable floor shape. The out-of-bag (OOB) error rate estimate increased from 8.62% (Tables 6 and7) to 17.82% (Tables 8 and 9) when the variable floor shape was removed.

Exit chipping, entrance shaving, kerf flare and break-away spurs are variables relating to the progression of the saw through the bone as opposed to variables that reflect class characteristics of the saw. The break-away spur was present in 48 (72%) of the specimens. Eleven (69%) of the test marks without a break-away spur were made with the 18 TPI saws. The analysts agreed on the location of the exit chipping on 38 (58%) of the specimens. Entrance shaving was observed by one analyst on one specimen. All three analysts agreed on the presence and location of the kerf flare in only one (2%) of the specimens.

Consistency of cut is an evaluation of the uniformity of the striations in a saw mark. Symes and colleagues (Symes 1993, Symes et al. 2010) indicate that a mechanically powered saw should generate a uniform striation pattern in a kerf wall while a manually powered saw should generate an erratic striation pattern. He further states that the consistency of cut is difficult to describe or measure, but easily illustrated. Because consistency of cut is difficult to measure or describe, number of directional changes within the striation pattern was used as a proxy for the variable. However, too few directional changes were observed in the saw marks (8 surfaces) to statistically test the relationship between the power source of the saw and the consistency of the cut. Of interest, the majority of the cut marks with striation directional changes (5 surfaces) were made with the mechanically powered saw.

Implication for Policy and Practice

Methods based on class characteristic recognition are subject to the same scientific standard as more quantitative methods such as DNA analysis, despite the qualitative nature of the analysis. This study presents a statistically sound approach for evaluating the reliability and accuracy of a class characteristic recognition method, and should serve as a model for testing similar methods. Also, it demonstrates through the tree classification and random forest classifier analyses avenues to statistically establish a ranking of multiple qualitative and quantitative variables. The end product, a decision tree, can be used to guide the analyst through the interpretation process to reach a conclusion based on sound science. This model is most valuable in cases with observed variables that are contra-indicators. The decision tree allows the analyst to weight the variables appropriately, without relying solely on experience and intuition. However, the saws included in this study were few. The reported low error rate may be more an indication of the limited number of possible answers (four saw types) rather than a true measure of the accuracy of the method. The next step is to repeat this study on a larger scale using more saw types and creating more saw marks.

INTRODUCTION

Statement of the Problem

Microscopic saw mark analysis is well researched, published and generally accepted. However, inadequate independent validation and an undefined potential error rate of the method limits its probative value. Without independent testing and a defined error rate, forensic evidence derived from use of the method does not meet the requirements for admissibility set forth by *Federal Rules of Evidence* (1975; 2000).

Literature Review

Published literature demonstrates the general acceptance of microscopic saw mark analysis, especially when applied to bone. Bonte published the seminal article that identified “practically all essential metric features of the saw used in a crime by examining the tool marks found on the bones” (Bonte 1975; p 322). Prior to Bonte’s work, saw mark analysis involved measuring the width of partial cuts, termed false starts. Bonte expanded his analysis to include the examination of the shape and pattern of striations observed in the wall of a saw mark. He disproved the then prevailing hypothesis that saw marks on bone destroy themselves with each consecutive stroke and showed that several class characteristics of the saw are recorded in the striation pattern. Bonte identified differences in the striations produced by the passive and power strokes. The passive stroke created a crude, deeper furrow resulting from all the saw teeth being pulled along a single level. The power stroke created a fine mark from each tooth that inclines slightly towards the passive furrow. The number of fine striations between each deep furrow reflected the number of saw teeth engaged in the stroke. Bonte found that the number of engaged teeth was usually two-thirds of the total number of teeth in the saw blade and that the number of deep furrows reflected the number of strokes completed. He also identified regularly spaced scratches, termed pull-out striations, that ran perpendicular to and crossed multiple layers of striations. These marks were produced by grazing teeth when a jammed saw was lifted out of a saw mark. Based on his research, the distance between these perpendicularly oriented striations recorded the distance between the teeth set to the corresponding side of the saw blade. Finally, Bonte briefly noted the potential to identify individual characteristics in a saw mark that revealed unique defects in the saw blade, but elaborated on the fact that class characteristics were more easily identified than individual characteristics (Bonte 1975).

Bonte's work was followed by Andahl (1978). Andahl also felt confident that an examiner could infer from the characteristics of a saw mark the type of saw which made it. He proposed a three step method when analyzing saw marks: 1) identify a possible saw type through detailed examination of the crime mark; 2) create test marks using the inferred saw type, or the suspect saw when available; and 3) compare the characteristics of the test mark to the crime mark. Andahl divided the crime mark into two components: the kerf floor and kerf wall. He found recorded in the kerf floor, both in false starts and on the breakaway spur of complete cuts, features that reflected the number of teeth per unit length, tooth set, degree of wear, direction of cut and condition of the blade. (Tooth set is the lateral bending of the teeth along the blade.) He also showed that the placement and condition of the striations impressed into the kerf wall reflected the tooth set. Andahl stated "a hacksaw will produce a series of regular striations whilst a rip saw produces very ragged lines" (Andahl 1978; p 37). Andahl recognized that the striation pattern observed in the kerf wall was complex and recommended creating a pencil rub of the cut surface using various amounts of pressure or pressing the cut surface on iodine impregnated paper to reduce the “noise”. Andahl stated that, when comparing the crime and test marks, the accuracy of the analysis was dependent on the amount of consistency between the two marks. He continued, “if the examiner is experienced and the crime mark contains sufficient detail then it will be found that only a blade with the same features will yield a test mark comparable with the crime mark” (Andahl 1978; p 40-41). Andahl stopped short of stating a specific weapon can be identified through a crime mark/test mark comparison, but stated “if the saw is damaged the evidential value of a positive comparison will be correspondingly higher” (Andahl 1978; p 44).

In 1992, Symes completed his dissertation titled *Morphology of Saw Marks in Human Bone: Identification of Class Characteristics* (Symes 1992). Using 26 types of saws and serrated knives, Symes made ten cuts with each saw/knife type in human long bone shafts. Through microscope analysis, he observed and described numerous features of the mark that reflected the class characteristics of the saw/knife. The majority of the features reflected the design of the saw, most notably tooth set and the distance between teeth. Other features recorded the progression of the saw through the bone and the power source of the saw: mechanical or manual. The end product of Symes work was a table of saw types and the corresponding class characteristics. For example, he listed a minimum kerf width, distance between kerf walls, as 0.055 inch for a 6 TPI crosscut saw (Symes 1992). However, he did not attempt to measure the strength of the correlation between each feature and the saw type, nor did he address the potential error rate.

In 2007, Saville et al. published a study that further expanded the discriminatory power of microscopic saw mark analysis (Saville et al. 2007). The authors conducted a two part study. First, three sawyers made saw cuts in pig femurs using four different types of saws. The researchers measured the kerf width recorded on 77 breakaway spurs and found it was distinct, but not unique. Several saw types produced the same saw mark width. Second, the authors compared saw marks made in nylon 6.6 (a bone substitute) using four new and five used Jackplus Hardpoint Handsaws. A mock crime mark was made with each saw by a single sawyer. Three additional sawyers made test marks with the same saws. Using an environmental scanning electron microscope (ESEM), the research team recognized a micro-striation pattern that was smaller than the deep furrows formed during the passive stroke and the fine striation formed during the power stroke. They found the distance between deep furrows to be 1-4 mm, the distance between fine striations to be 30-400μm and the distance between micro-striations to be smaller than 1μm. Using the micro-striation patterns, the researchers matched the test marks to the mock crime marks without error. From these results, the authors concluded that the micro-striations were individual characteristics that reflect unique defects in the saw teeth and can be used to match a particular saw to a crime mark (Saville et al. 2007).

In 2010, Freas designed a study to evaluate the affect of saw wear on the expression of features in the saw mark (Freas 2010). She examined consecutive cuts made in bone using a crosscut saw and hacksaw with light and scanning electron microscopes (SEM). The author found that the striations, especially the fine striations of the power stroke, became less defined with each consecutive cut and the associated wear of the saw teeth. The loss of detail was more significant in the saw marks made with the crosscut saw than the hacksaw. She hypothesized that the difference was due to the material hardness of the saw blade; a crosscut saw is designed to cut wood and a hacksaw is designed to cut metal. Despite the loss of detail, Freas identified tooth hop, waves in the striations, in the saw marks made with the worn saws, allowing her to conclude that a saw mark made with a worn saw was eligible for analysis. Contrary to Saville et al. (2007), Freas found that the SEM was not analytically valuable in analyzing saw marks on bone (Freas 2010). She found that the high powered magnification obscured the overall pattern of striations important for class characteristic recognition.

Recently, researchers have focused on applying microscopic saw mark analysis to compromised bone (Pope and Smith 2004; Marciniak 2009). Pope and Smith examined experimentally induced saw marks in burned skulls (2004). The saw marks were easily recognized in the burned specimen. Marciniak also examined saw marks on burned bone (2009). She found that thermal destruction affects the visibility and recognition of saw mark striations, but that false starts were well-preserved in thermally damaged bones. She concluded that valuable class characteristics of the saw mark are present on cremated bones (Marciniak 2009).

In addition to the general acceptance, publications have shown that the microscopic saw mark analysis has played an important role in medicolegal investigation. In her 1998 text, *Forensic Osteology: Advances in the Identification of Human Remains,* Reichs showcased six dismemberment cases in which microscopic saw mark analysis was successfully performed (Reichs 1998). In the same textbook, Symes and colleagues present a high profile medicolegal case in which microscopic saw mark analysis was performed (Symes et al 1998). Symes alone has reported performing microscopic saw mark analysis in approximately 200 dismemberment cases (Morton 2006). Furthermore, testimony based on the use of microscopic saw mark analysis has been admitted into evidence in criminal trials (*State of Texas vs. Timothy Wayne Shepherd*).

Despite the general acceptance of microscopic saw mark analysis and the admission of evidence based on the method in criminal proceedings, there is a significant gap in the research: defining of the potential error rate. Both Symes and Andahl address the inherent uncertainty of microscopic saw mark analysis (Symes 1992; Andahl 1978). Andahl states, "In the case of saw marks the degree of success achieved will be very dependent on the experience the examiner has of this type of work and his/her skill at pattern recognition" (Andahl 1978; p. 32). Symes identifies specific difficulties when differentiating true striations curvature from mimics and measuring a single tooth trough width (Symes 1992). Symes cautions that an error of 0.01 inch in a tooth trough width measurement is significant when sorting saws by tooth size. Regardless of these concerns, practitioners apply microscopic saw mark analysis to forensic evidence without addressing the potential error rate (Bonte 1975; Andahl 1978; Symes 1992; Reichs 1998; Symes et al. 1998; Pope and Smith 2004; Saville et al. 2007; Marciniak 2009; Freas 2010).

Rule 702 of the *Federal Rules of Evidence* (1973, 2000) establishes that an expert witness may testify in the form of an opinion if: a) the testimony will help the trier of the facts to understand the evidenced or to determine a fact in issue; b) the testimony is based on sufficient facts or data; c) the testimony is the product of reliable principles and methods; and d) the expert has reliably applied the principles and method to the facts of the case. The *Daubert v. Merrel Dow*

Pharmaceuticals, Inc (1993) trial had a direct affect on *Rule 702*. Prior to *Daubert,* trial judges deferred to general acceptance in a particular field as a measure of admissibility. In response to *Daubert,* trial judges' role evolved into one of gatekeeper by way of excluding expert testimony based on unreliable science. To meet the newly defined role, judges often hold pretrial hearings on the validity of the science in question, typically called Daubert hearings. A Daubert hearing is a five-pronged test that asks: 1) if the theory or technique can be and has been tested; 2) has the theory or technique been subjected to peer-review and publication; 3) is the known or potential rate of error defined; 4) are there existence and maintenance of standards controlling the technique's operation; and 5) does the theory or technique enjoy general acceptance within a relevant scientific community. These factors are set forth as guidelines with the recognition that they are neither exclusive nor dipositive. However, they serve the scientific community as a well-formed checklist for measuring the strength of a scientific method. Currently, microscopic saw mark analysis does not meet all the factors of the Daubert test, specifically there is no defined known or potential error rate.

Rationale for the Research

In light of federal requirements of scientific evidence, the authors have designed a validation test of the generally accepted method of microscopic saw mark analysis. The goals of the study are to independently validate the method, identify the inherent error rate of the method and disseminate the results in a peer-reviewed journal. The objective of the study is to bring the method in line with the criteria set forth by *Rule 702* of the *Federal Rules of Evidence* and the Daubert test.

MATERIALS AND METHODS

Test saw marks were made in bones and analyzed using a Keyence VHX-1000 Digital Light Microscope with 5 – 50x lens (Osaka, Japan). Four morphologically different saws were chosen for the study. The saw brand and blade descriptions are listed in Table 1.

TABLE 1 – Saw Brands and Blade Descriptions

Saw	Tooth Set	TPI	Direction of Cutting Stroke	Power Source
Stanley FaxMax Crosscut Saw (Crosscut)	Alternating	8	Push	Manual
Nicholson Wavy Blade Hacksaw (Wavy)	Wavy	18	Push	Manual
Nicholson Raker Blade Hacksaw (Raker)	Raker	18	Push	Manual
Black and Decker Fire Storm Reciprocating Saw (Reciprocating)	Raker	10	Push	Electric

Four anatomically gifted human femurs were used in the study (Fig. 1). The femurs were previously frozen and some muscle remained adhered to the bone. Prior to the study, each femur was thawed in a refrigeration unit. Each saw was assigned to one of the four femurs and only one saw was used on each bone. Fifteen test marks were made with each saw, except for the reciprocating saw. Only 13 saw marks were made with it; the amount of bone consumed with each cut was too great to allow for 15 cuts. Each bone was anchored to a laboratory bench with clamps during the sawing. Two sawyers created the test marks; each held the clamped end of the bone with one hand and powered the saw, or steadied it in the case of the reciprocating saw, with the other. Each test mark (specimen) consisted of a false start and a complete cut (Fig. 2). The false starts were made with five consecutive power strokes. The reciprocating saw is an electrically powered saw and the number of power stokes could not be accurately counted. For consistency, the sawyer attempted to make the reciprocating saw false starts equal in depth with the false starts made with the manually powered saws. The test marks were separated from each other using a surgical saw. The surgical saw cut surfaces were scored to insure they were not mistaken as a test cut surface.

FIG. 1-Shown are the femurs used in the study.

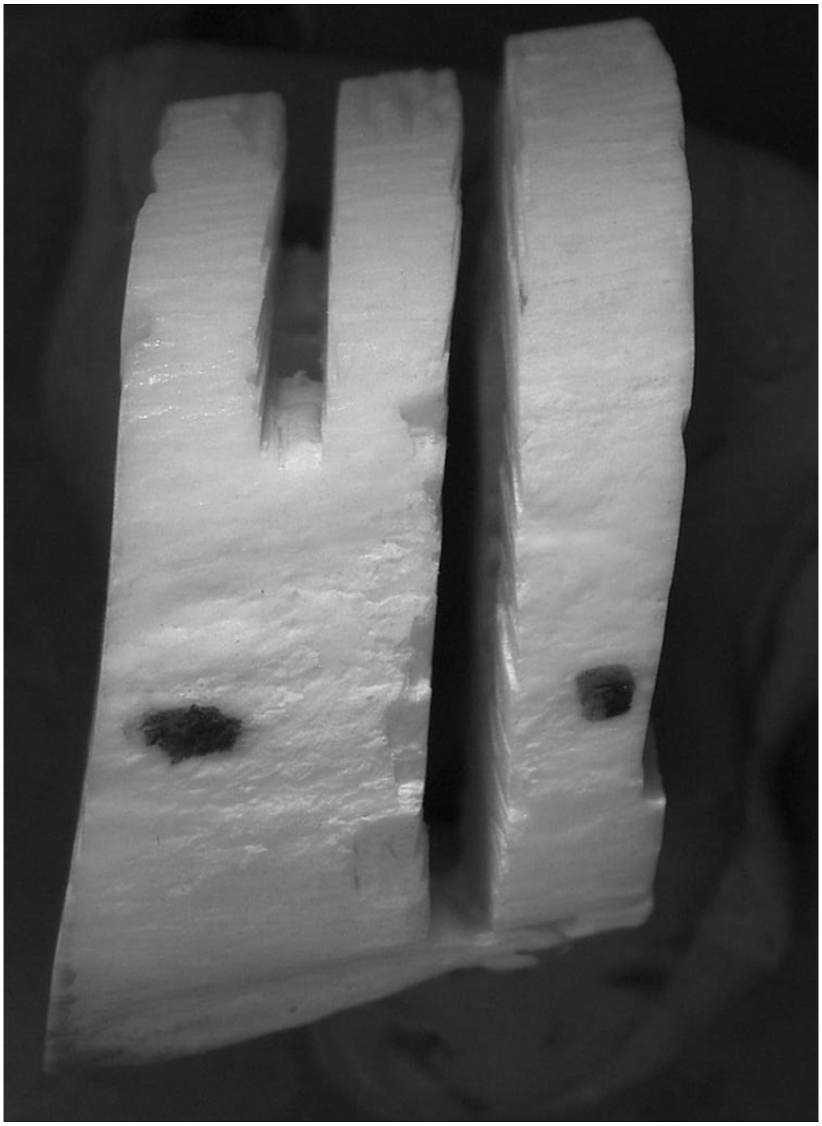

FIG. 2-Shown is a test mark (specimen) consisting of a false start (left) and a complete cut (right). Note the black ink dots on the surface of the bone. The ink was placed on each test mark to designate a marked and unmarked surface for recording several variables.

Each test mark was randomly assigned a specimen number from 1-58. Then, each mark was processed in a water-soap bath at 70C for 24 hours. The soap used was Superkleen (Delta Foremost; Memphis, TN) and the concentration was approximately 1/3 soap to 2/3 water. The first test mark of each femur was made at the level of the lesser trochanter. The muscle adhered to the specimen required it to be processed for an additional 24 hours. One side of each specimen, perpendicular to the false start and break away spur axis, was marked with a dot of black ink (Fig. 2).

The digital microscope and dual-arm fiber-optic light source (Schott; Auburn, NY) were used to evaluate the features of the test marks. The measuring function of the Keyence software was used to measure the quantitative variables. The microscope was calibrated each day prior to analyzing the specimens. The indirect light generated by the optic light box and the high density resolution function of the Keyence software were used to enhance the features of the test mark (Fig 3).

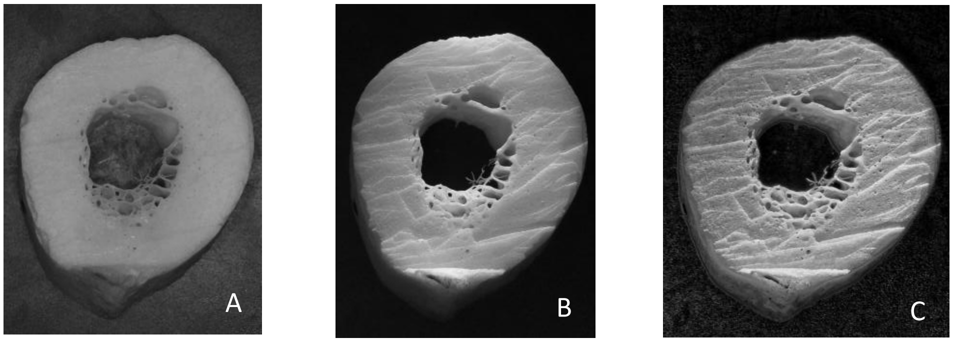

FIG. 3-Photographs of a cut surface taken with the Keyence microscope using (A) direct lighting (B) indirect lighting and (C) high density resolution.

Fifteen variables were evaluated in each specimen. Appendix A describes each variable and how it was evaluated and recorded. Table 2 provides a list with an abbreviated description of each variable. The variables observed in the wall of the saw mark (pullout striations, consistency of cut, tooth hop and harmonics) were scored only on one side of the complete saw mark. The surface of the saw mark that abutted the false start was analyzed for these variables. Three doctoral level anthropologists examined each specimen independently. Each analyst has a minimum of six years of experience analyzing tool marks in bone and cartilage and participated in a knife cut mark validation study (2008-NI-CX-0004). To ensure that each analyst understood the variables, a pilot study of 10 saw marks was conducted. The results were reviewed by the analysts and variable definitions were refined to limit ambiguity.

TABLE 2 – List of Variables Recorded and Abbreviated Descriptions*

Variable	Description
Minimum Kerf Width	Minimum distance across the false start
Kerf Wall Shape	Description of the false start wall alignment when viewed in the normal plane
Trough Morphology	Shape of the floor of the kerf when viewed in the normal plane
Tooth Width	Dimensions of the tooth grooves observed on the kerf floor
Trough Width	Width of the trough at the kerf floor
Floor Dips	Distance between peaks observed on the kerf floor (false start or break-away spur)
Kerf Floor Shape	Shape of the kerf floor when viewed perpendicular to the normal plane
Pullout Striations	Distance between scratches that run perpendicular to the striations on the kerf wall
Consistency of Cut	Number of directional changes of the striations across the kerf wall
Tooth Hop	Distance between peaks in the striations observed in the kerf wall
Harmonics	Distance between peaks observed three-dimensionally in the kerf wall
Break-away Spur	Spur of bone at the endpoint of a complete saw cut
Kerf Flare	Flaring of the false start at one end
Entrance Shavings	Polishing of the margins of the kerf wall
Exit Chipping	Small divots in the margins of the kerf wall

*The first 11 variables listed reflect class characteristics of the saw mark; the last four reflect the progression and direction of the saw through the bone.

Descriptive analysis was performed using the Microsoft Excel 2007 statistical package. The data were further analyzed with classification trees and random forests grown with the “rpart” and “randomForest” libraries of the open source data analysis package R (www.r-project.org). All data obtained from all three analysts were included in the statistical analysis. Two classification trees were grown. The first classification tree was grown using the variables floor shape, wall shape, minimum kerf width and average tooth hop. The second classification tree was grown using the variables wall shape, minimum kerf width and average tooth hop. Confusion matrices, measurement of correct and incorrect classifications, were generated with the training data to estimate the error rate associated with each tree. Using the same sets of variables, two random forest classifiers were generated to identify the out-of-bag (OOB) estimate of error rate and variable importance.

RESULTS

The study design resulted in 58 specimens. The statistical analyses of the data show several variables to be replicable and informative in the classification of saw type. Minimum kerf width was highly consistent between the three analysts (Fig. 4). Furthermore, minimum kerf width varied significantly by saw type (Fig. 5). The kerf floor shape was another informative variable when coded as W-shaped. Perfect agreement was obtained between the crosscut saw and a W-shaped floor by all three analysts. In contrast, there was nearly no association of the floor shape (rounded or flat) and the saw type (raker set hacksaw, wavy set hacksaw, and raker set reciprocating saw) (Table 3). Tooth hop was recognized by all three analysts on 41 (71%) of the cut surfaces. Plotting of average tooth hop measurement showed little variation between the three analysts (Fig. 6). In eight (14%) of the saw marks all three analysts identified a change in cut direction. Five (63%) of these marks were created by the reciprocating saw. The maximum number of directional changes observed in a reciprocating saw mark was four. The other marks were created with the crosscut saw (x1) and wavy set hacksaw (x2); only one directional change was seen in each of these marks.

Several of the variables were too infrequently observed to be statistically evaluated in this study: trough morphology; kerf flare; pullout striation; entrance shavings; and harmonics. A trough floor other than flat was recorded by one analyst once. Kerf flare was identified in only 18 (10%) specimens by the three analysts. Pullout striations were observed by all three analysts in only 3 (5%) specimens. Entrance shavings and harmonics were not identified by all three analysts in any of the saw marks.

The classification tree grown on the variables floor shape, wall shape, minimum kerf width and average tooth hop demonstrated that floor shape and minimal kerf width were informative variable in saw classification (Fig. 7). Table 4 shows the confusion matrix associated with the tree. The classification tree grown on wall shape, minimal kerf width, and average tooth hop showed that minimum kerf width was the most informative variable in saw classification (Fig. 8). The confusion matrix is shown in Table 5.

Two random forest classifiers were performed. The first classification tree was grown using the variables: wall shape, minimum kerf width, floor shape and average tooth hop. The second classification tree was grown removing the variable floor shape. The OOB error rate estimate increased from 8.62% (Tables 6 and7) to 17.82% (Tables 8 and 9) when the variable floor shape was removed.

Exit chipping, entrance shaving, kerf flare and break-away spurs are variables relating to the progression of the saw through the bone as opposed to variables that reflect class characteristics of the saw. The break-away spur was present in 48 (72%) of the specimens. Eleven (69%) of the saw marks without a break-away spur were made with the 18 TPI saws. The analysts agreed on the location of the exit chipping on 38 (58%) of the specimens. Entrance shaving was observed by one analyst on one specimen. All three analysts agreed on the presence and location of the kerf flare in only one (2%) of the specimens.

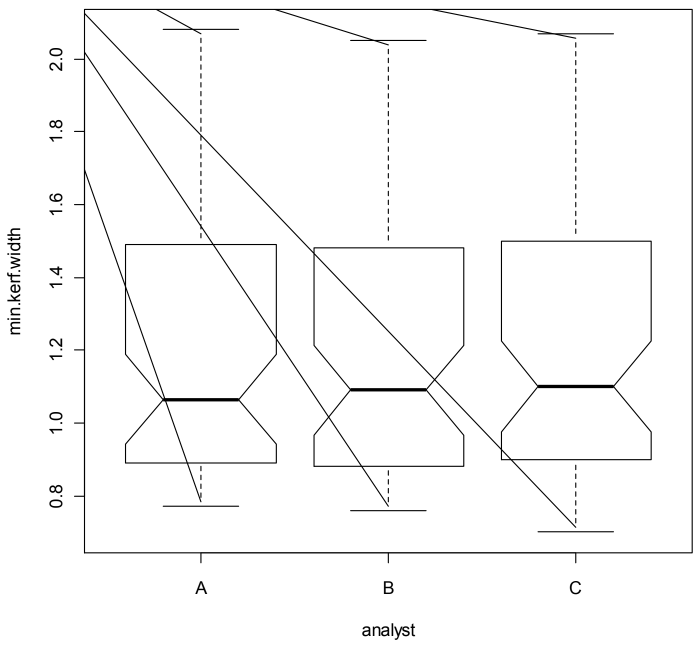

FIG. 4-Box and whisker plots of the distribution of the minimal kerf width of all saw marks by analyst. The minimum kerf width is recorded in mm (y-axis scale). The three horizontal lines in the central boxes mark the quartiles and median. The whiskers extend to the most extreme value. Note the near alignment of the median for each box demonstrating the consistency of the measurement between the analysts.

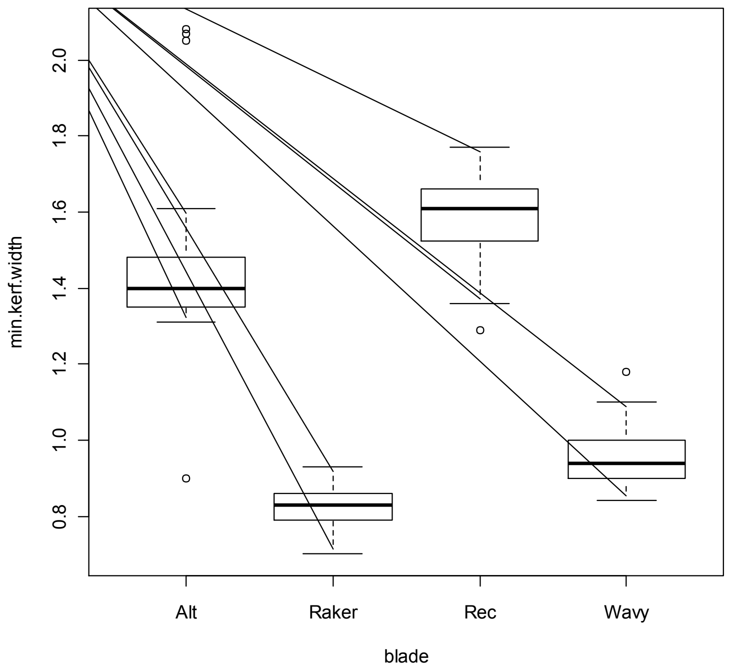

FIG. 5-Blox and whisker plots of the distribution of the minimum kerf width segregated by saw blade type: ALT – 8 TPI crosscut blade; Raker – 18 TPI raker set hacksaw; Rec – 10 TPI raker set reciprocating saw; Wavy – 18 TPI wavy set hacksaw. The minimum kerf width is measured in mm. The three horizontal lines in the central boxes mark the quartiles and median. The whiskers extend to the most extreme value or to a distance of 1.5 times the interquartile range from the nearest quartile. Individual outliers above or below the whiskers are marked with circles.

TABLE 3 – Confusion Matrix of Floor Shape and Saw Type

		Floor Shape		
Saw Type		Flat	Rounded	W-shaped
	Crosscut	0	0	45
	Raker Set Hacksaw	31	14	0
	Wavy Set Hacksaw	26	19	0
	Raker Set Reciprocating Saw	20	19	0

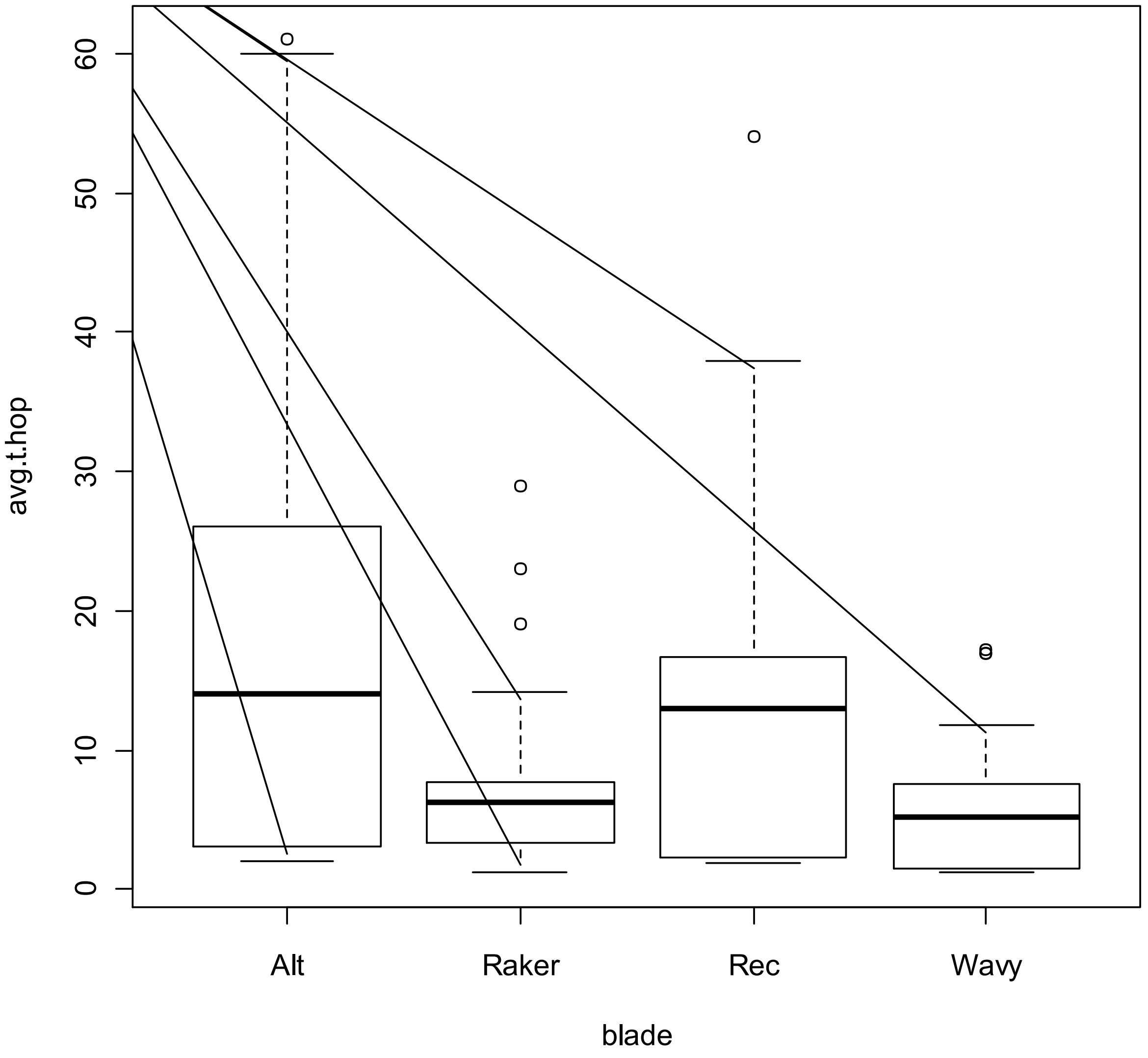

FIG. 6-Box and whisker plots of the distribution of average tooth hop by analyst. The variable is recorded in mm (y-axis scale). The three horizontal lines in the central boxes mark the quartiles and median. The whiskers extend to the most extreme value. Individual outliers above or below the whiskers are marked with circles.

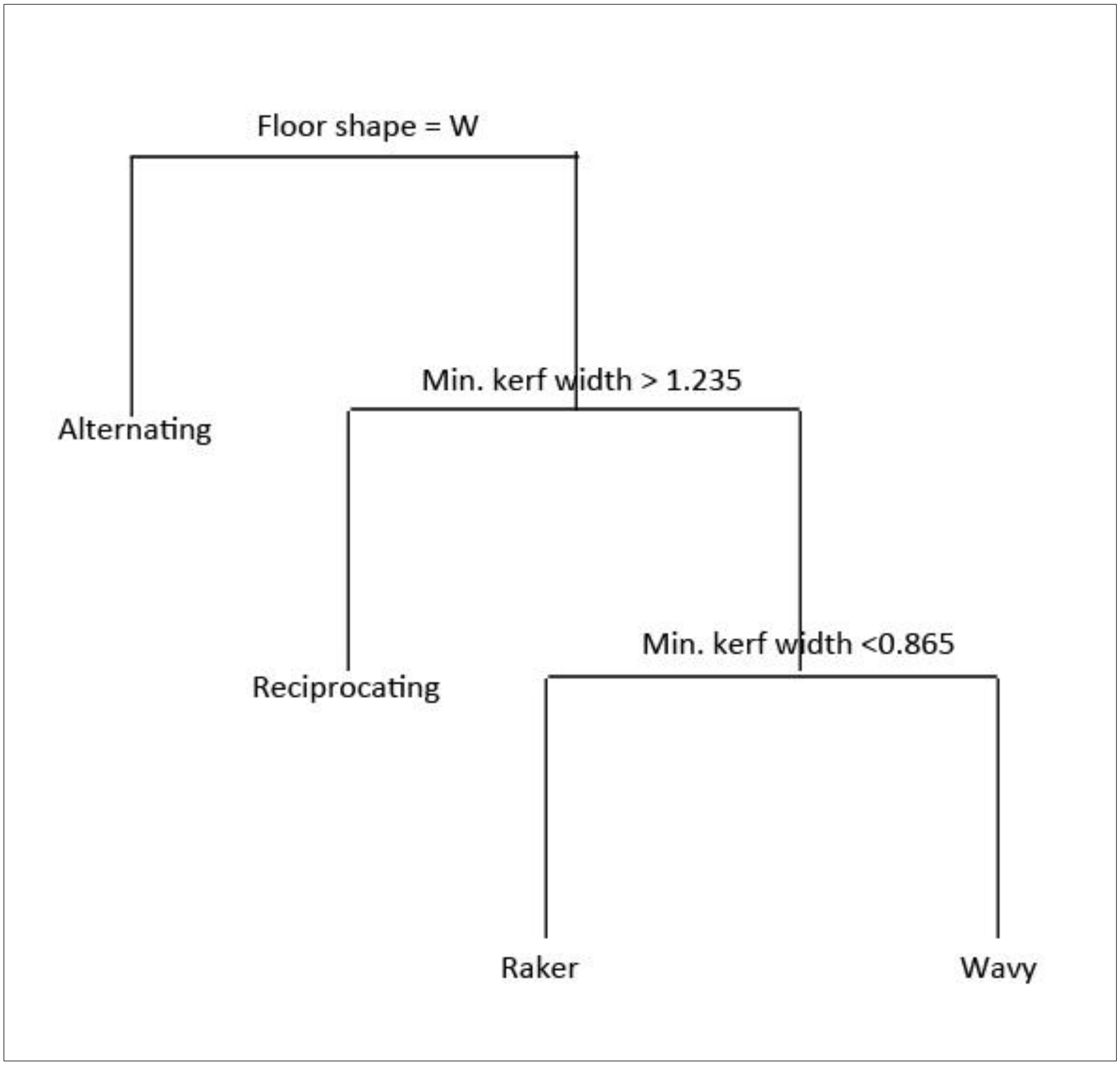

FIG. 7-Classification tree modeled on floor shape, wall shape, minimum kerf width and average tooth hop.

TABLE 4 - Confusion Matrix Associated with the Classification Tree shown in FIG. 7

	Alternate	Raker	Reciprocating	Wavy
Alternating	45	0	0	0
Raker	0	37	0	8
Reciprocating	0	0	39	0
Wavy	0	4	0	41

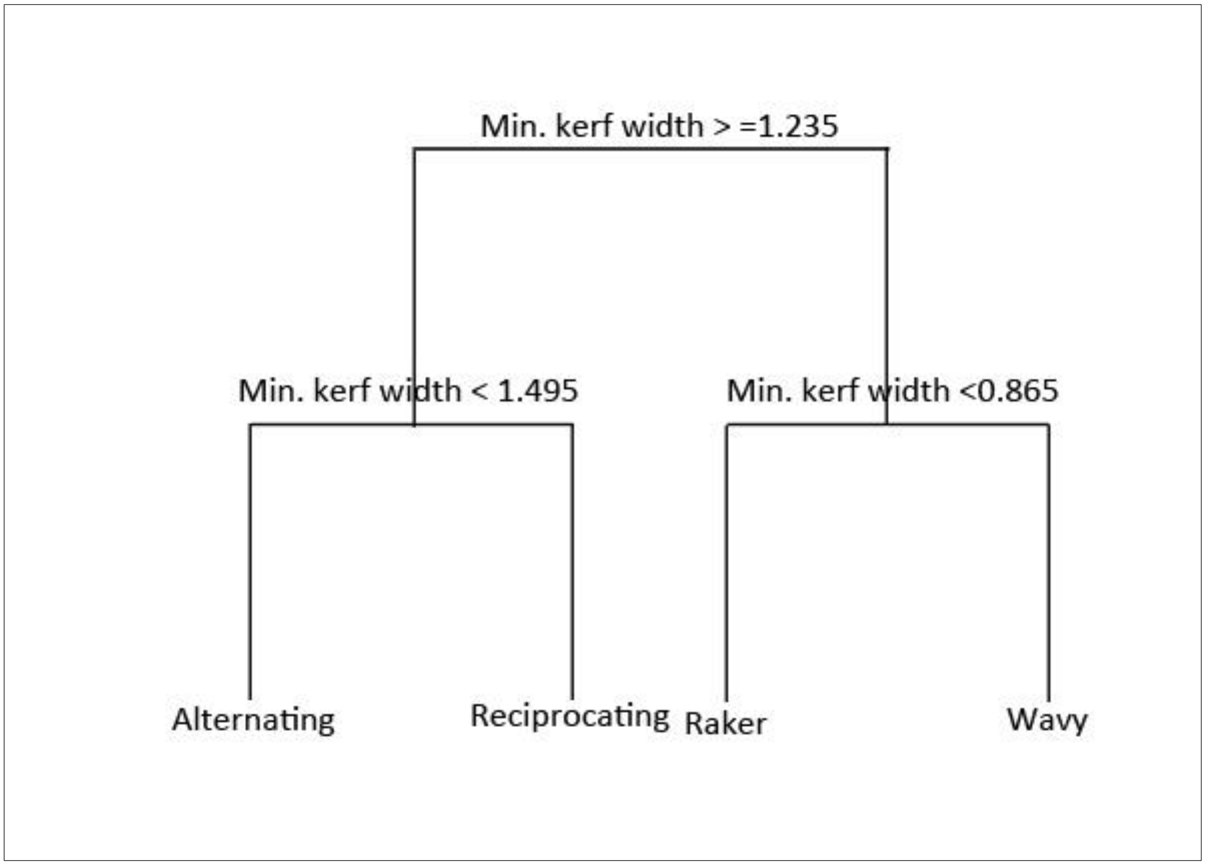

FIG. 8 - Classification tree modeled on wall shape, minimum kerf width, and average tooth hop.

TABLE 5 - Confusion Matrix Associated with the Classification Tree shown in FIG. 8

	Alternate	Raker	Reciprocating	Wavy
Alternating	35	0	9	1
Raker	0	37	0	8
Reciprocating	6	0	33	0
Wavy	0	4	0	41

TABLE 6 – Confusion Matrix for the Random Forest Classifier Modeled on Wall Shape, Minimum Kerf Width, and Average Tooth Hop

	Alternate	Raker	Reciprocating	Wavy
Alternating	45	0	0	0
Raker	0	38	0	7
Reciprocating	0	0	39	0
Wavy	0	8	0	37

TABLE 7 - Variable Importance after the Random Forest Classifier Modeled on Wall Shape, Minimum Kerf Width, and Average Tooth Hop

Variable	Importance
Minimum Kerf Width	68
Floor Shape	39
Wall Shape	11
Average Tooth Hop	9

TABLE 8 – Confusion Matrix for the Random Forest Classifier Modeled on Minimum Kerf Width, and Average Tooth Hop

	Alternate	Raker	Reciprocating	Wavy
Alternating	37	37	1	7
Raker	0	40	0	5
Reciprocating	11	0	28	0
Wavy	0	7	0	38

TABLE 9 – Variable Importance After the Random Forest Classifier Modeled on Minimum Kerf Width, and Average Tooth Hop

Variable	Importance
Minimum Kerf Width	65
Average Tooth Hop	20
Wall Shape	14

Conclusion

Discussion of Findings

The study was designed to validate the method of microscope saw mark analysis. Four different saw types that represented four major classes of class characteristics were chosen for the study. The saw types varied in tooth set (raker, wavy and alternating), TPI and power source (mechanical and manual). Some of the saw types overlapped in one characteristic, while varying in another. For example, the two hacksaws had the same TPI but with different tooth set and the two raker set saws differed in TPI and power source. This design enabled the investigation of the variables at a finer-grained level.

Analysis of the class characteristics was done using random forest classification. A random forest classifier is built by constructing a large number of classification trees on a set of training data and passing new cases down each tree. The class having a plurality of votes at the end of the procedure is the predicted class of a new case. Random forest classification was first proposed by Ho (2002) and Breiman (2002) and first implemented in Fortran by Breiman and Adele Cutler. A complete detailed description of the method along with its many options and by-products is available at

http://www.stat.berkeley.edu/~breiman/RandomForests/cc_home.htm

Additional results on statistical properties of the method, e.g., consistency of the class proportion estimators, are cited therein. The adaptation for R of Breiman's and Cutler's algorithm is due to Liaw and Wiener (2002).

The goal of utilizing random forests is not to develop a classification procedure, but to use the method to estimate the amount of information for blade type classification contained in observed characteristics of saw marks on bone. Furthermore, the goal is to determine the relative importance of the study variables in classification of blade types. The first objective is facilitated by the "out of bag" (OOB) estimates of classification accuracy. Each tree in the forest is grown from a bootstrap sample of size equal to the number of cases in the study. About one third of each bootstrap sample is reserved as the set of OOB cases and these are classified after the tree is grown from the remaining data. A tally of the number of times each case in the study was OOB and assigned to each class is maintained throughout the construction of the forest. At the end of the construction, this process results in an estimate of classification accuracy (or, equivalently, of the classification error rate) and a confusion matrix tabulating the number of times cases belonging to each class were assigned to the correct class and the other candidate classes. The estimate of classification accuracy is regarded as a measure of the information for classification contained in the study variables for the particular saws in the study. Generalization to a larger population of saws is problematic and our accuracy estimates should be considered at best an upper bound for a larger population.

As a tree is grown for the random forest classifier, each node of the tree is split into daughter nodes by choosing the best split obtained from a randomly chosen subset of the input variables. The number of variables selected for each split is an adjustable parameter with a default value of roughly the square root of the number of available input variables. The best split is the one that results in two daughter nodes the sum of whose Gini impurity measures is the smallest possible. The Gini measure for a single node is

where the sum is over all classes , is the proportion of cases at the node belonging to class and is the number of cases at the node. It can be shown that any split results in daughter nodes whose total Gini measure is smaller than the Gini measure of the parent. A simple index of the importance of a variable is the average decrease in the Gini measure when that variable is used in a split in developing the whole forest. The Breiman-Cutler procedure allows more intricate measures of variable importance, but in our study the average Gini decrease gave sufficiently clear cut rankings of importance and others were not employed.

Missing values in the study variables are filled in first with a rough imputation procedure that substitutes the median of numeric variables and the mode of categorical variables. As the forest is developed, these imputed values are adjusted with weighting by proximities to other cases without missing values. These proximities are a very useful component of the random forest output, but in our study the variables eventually selected did not have many missing values and the imputation procedure was not critical.

Based on the variables observed in the saw marks, the study results showed that minimum kerf width, W-shaped floor, and average tooth hop are highly replicable variables. Random forest modeling showed that minimum kerf width, floor shape, wall shape and average tooth hop are important variables of the saw mark for classifying the saw type. Furthermore, in this study of 58 specimens made with four saw types, accuracy in saw type identification ranged between 83 – 91%. The results of the study are supportive of microscopic saw mark analysis to identify saw class characteristics.

The application of the statistical model used in this study, enables the measurement of an error rate as shown. However, this error rate is not directly comparable to the application of the method in absence of the statistical approach. The classification trees follow algorithms that mimic human decisions making but force the final classification into the lowest possible tool-class. In the traditional approach to microscope saw mark analysis, the analyst navigating the observed class characteristics in a manner similar to classic clinical diagnosis from a physical exam. The analyst is free to stop the analysis at any point along the decision tree. In this regard, the analyst may achieve a higher accuracy rate by limiting the granularity of the analysis.

Unfortunately, many variables that are identified as informative class characteristics by previous researchers (Symes 1992 and Symes et al. 2010) were not or were rarely observed in this study, these include: trough morphology, tooth width, floor dips, kerf flare, pull-out striations and harmonics. Typically, trough morphology, tooth width and kerf flare are observed in a false start. The study method required each false start to be created with five powered strokes. The resulting kerfs were deep. The images Symes (Symes 1992, Symes et al 2010) used to demonstrate trough morphology, tooth width and kerf flare, are of very shallow false starts. Also, fine scratches adjacent to the false start were observed on a few specimens and showed features of the trough morphology and individual tooth marks that were absent in the associated deep false starts. As per the method, these incidental scratches were not analyzed. Therefore, the absence of individual tooth marks, rare kerf flare and limited variation in trough morphology were most likely a result of the study design and not the variables themselves. However, the study results indicate that trough morphology, tooth width and kerf flare should not be recorded in the absence of shallow false starts.

Pull-out striations occur when the saw is withdrawn from the kerf mid-stroke and reflect the distance between the teeth that score the surface (Symes et al. 2010). For alternating tooth set saws, pull-out striations represent the distance between two teeth. For raker tooth set saws, they represent the distance between three teeth. Therefore, pull-out striations, in conjunction with other characteristics of the mark, can be used to determine the number of teeth per inch. The study method was not designed to purposely create pull-out striations, but the instability of the clamped fresh bone caused the saw to be removed from and returned to partial cuts with nearly every cut which should have created numerous pull-out striations. Despite this occurrence, all three analysts observed pull-out striations on only four saw marks. Furthermore, the inter-observer error of the pull-out striation distances measured in the three saw marks ranged from 0.06 – 4.03 mm. As a result, the authors caution against using pull-out striations as an indicator of teeth per inch until the accuracy and precision of the variable is more thoroughly studied.

Consistency of cut is an evaluation of the uniformity of the striations in a saw mark. Symes and colleagues (Symes 1993, Symes et al. 2010) indicate that a mechanically powered saw should generate a uniform striation pattern in a kerf wall while a manually powered saw should generate an erratic striation pattern. He further states that the consistency of cut is difficult to describe or measure, but easily illustrated. Because consistency of cut is difficult to measure or describe, number of directional changes within the striation pattern was used as a proxy for the variable. However, too few directional changes were observed in the saw marks (8 surfaces) to statistically test the relationship between the power source of the saw and the consistency of the cut. Of interest, the majority of the cut marks with striation directional changes (5 surfaces) were made with the mechanically powered saw.

The use of the classification tree method in measuring the potential error rate associated with a class characteristic based method has been demonstrated previously (Love et al. 2012). The classification tree model enables the analyst to decide which saw type made a given saw mark or associate probabilities with each of the given saw types for a specific saw mark. The decision or probability assessment is based on the observed values of variables such as those described above: floor shape and kerf width. The plots and tables provided in the preceding section indicate that these variables separately convey information about saw type. However, they do not tell us how to optimally combine the variables to derive a decision rule or estimation procedure for new cases. The classification tree enables this process.

The study presented here has several limitations and strengths. The number of saw types included in the study is few. Several of the variables often observed on crime marks were absent from the experimental marks; as a result, their value in accurate identification of saw type could not be measured. The error rates identified through this study are specific to the four saw types used and the variables observed. The strength of the study is that it presents a statistically sound approach to measure the potential error rate associated with it. The majority of the literature presenting microscopic saw mark analysis describes studies that tweak the method. This is true of the Saville et al. study, in which the authors identified a new variable and Marciniak who investigated saw marks in burned bone (Saville et al. 2007; Marciniak 2009). Both of these studies fail to independently validate the current method, and they do not address error rate.

Furthermore, Symes and colleagues undertook a large project funded by the National Institute of Justice to train law enforcement, medical examiners, and coroners in the use of microscopic saw mark analysis in bone specimens. The authors identified three shortcomings of microscopic saw mark analysis: “(1) a lack of research, (2) a related lack of standard terminology, definitions and protocols for the documentation and analysis of this evidence, and (3) as a consequence, a poor understanding and awareness among the forensic community regarding the evidentiary value and possibilities of this type of physical evidence” (Symes et al. 2010; Abstract, no page number). Although the authors stated later in the report, “increased necessity for scientific work to meet Daubert Standards in the courtroom has provided impetus for [their] study”, they failed to mention absence of validation studies and a defined error rate as additional weaknesses of the method (Symes et al. 2010; p. 22). Through the training and testing of analysts in the method, the authors measured a 30% error rate. However, this error rate reflected the ability of the trainees, not the error rate associated with the method.

In light of this limitation, another strength of the presented study is the decision tree, the end product of the statistical model. Traditionally, microscope saw mark analysis is done by recording a number of class characteristics and interpreting the characteristics to derive a saw class. Not all saw marks demonstrate all characteristics clearly and a mosaic expression of characteristics occurs. Therefore, the final classification of the saw type is strongly based on the analyst's experience. The potential error rate cannot be measured when the accuracy of an analysis is analyst specific (based on experience); each analyst is expected to have a different potential error rate. In order to measure the error rate associated solely with the class characteristics and not the analyst's experience in a statistically sound manner, the classification tree model was used. The classification tree removes the analyst from the interpretation stage of the analysis, where experience plays the strongest role, allowing the potential error rate based only on the class characteristics to be measured. An outcome of the statistical approach is a decision tree that ranks the importance of the variables and demonstrates their relationship. Use of the decision tree can transform an experience based method into a more empirically based method. The decision trees included in this manuscript are specific to the four saw types used and variables observed. For a decision tree to be applicable to forensic casework it must be grown on more saw types and include infrequent observed variables.

Implication for Policy and Practice

Methods based on class characteristic recognition are held to the same scientific standard as more quantitative methods such as DNA analysis, despite the qualitative nature of the analysis. This study presents a statistically sound approach to evaluating the reliability and accuracy of a class characteristic recognition method, and should serve as a model for testing similar methods. Also, it demonstrates through the tree classification and random forest classifier models avenues to statistically establish a ranking of multiple qualitative and quantitative variables. The end product, a decision tree, can be used to guide the analyst through the interpretation process to reach a conclusion based on empirical data. This model is most valuable in cases with conflicting observations; such as floor shape indicative of an 8 TPI crosscut saw and a minimum kerf width indicative of a 10 TPI raker set reciprocating saw. In this situation, the decision tree allows the analyst to weight the variables appropriately, without relying solely on experience and intuition.

However, as stated previously, the number of saws included in the study is few. The reported low error rate is an indication of the limited number of possible answers (four saw types) rather than a true measure of the accuracy of the method. Also, the error rate is specific to the random forest classifier statistical model and not the applicable to the traditional method of differential typology based on a suite of characteristics. The next step is to repeat this study on a larger scale using more saw types creating more saw marks. The authors caution against the tendency to solely continue to seek new variables that may improve the method. Although expanding the methods is a worthy endeavor, it should not be done at the expense of independent validation of the current method.

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Dissemination

Forensic anthropologists are the target audience for the dissemination of the study results. The project's greatest impact in the field of forensic anthropology is the presentation of a statistically sound evaluation of a historically well-accepted method. The details of the materials and method, raw data and statistical analysis were presented at the American Academy of Forensic Sciences 64th Annual Meeting. In addition to the release of this final report, a manuscript will be submitted to the Journal of Forensic Sciences.

Appendix A

Definitions and Illustrations of Variables

Break-Away Spur

The break-away spur is a projection of uncut bone at the terminal end of the cut. Features observed in a false start kerf floor are often observed in the break-away spur as well.

The break-away spur is coded as Present or Absent.

False Start Kerf

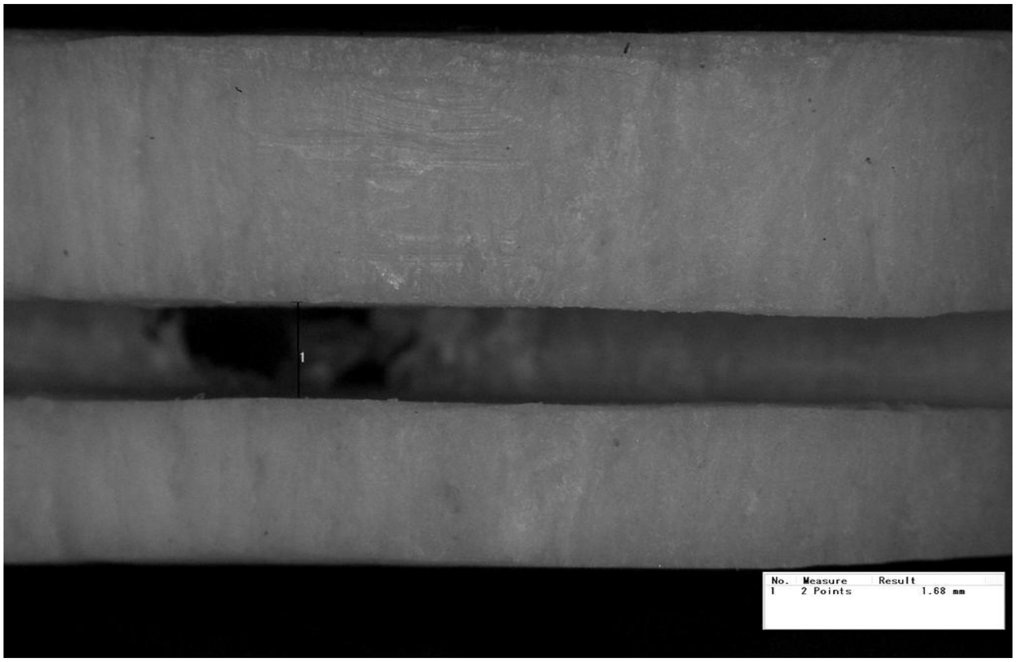
False start kerfs are cuts that do not completely section the bone and are composed of two initial corners, two walls, two floor corners, and a floor

Every specimen has a false start by research design; this feature is not recorded.

Minimum Kerf Width

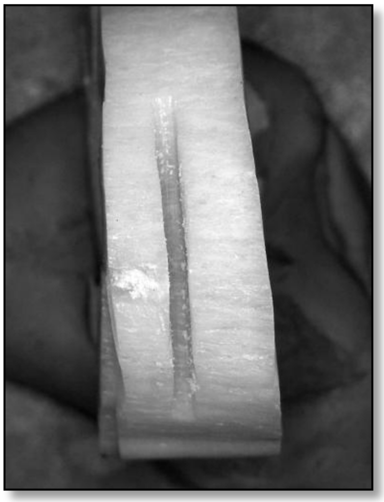
Minimum kerf width is the minimum width from kerf wall to kerf wall. The minimum kerf width is directly related to the width of the tooth set of the blade.

The minimum kerf width of each false start kerf is measured in mm. Only one measurement is taken per kerf.

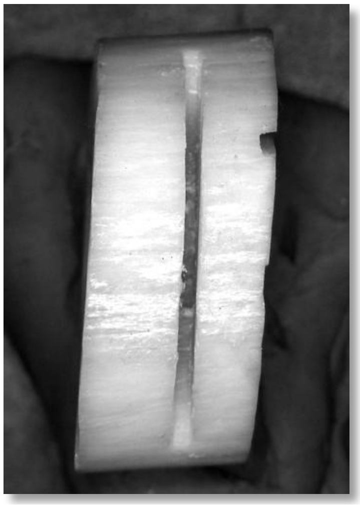


Kerf Wall Shape

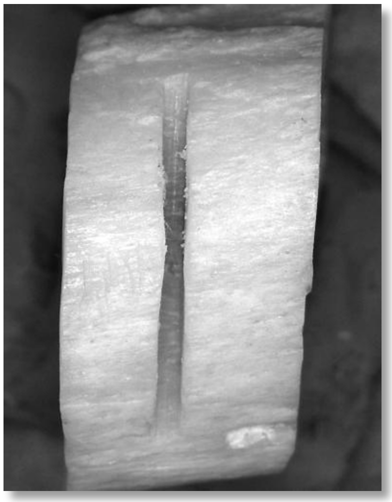
Kerf shape is a description of the outline of the false start when viewed in the normal plane. The kerf shape is wavy, straight, or narrowing. A wavy kerf has an hour glass shape and may have islands in the tooth trough (see tooth trough below). A narrowing kerf has straight walls that narrow and expand from a defined point. The kerf shape is recorded as **W**avy, **S**traight, or **N**arrowing.



Wavy



Straight



Narrowed

Kerf Flare

Kerf flare is observed on the kerf floor at the very end of the false start. The feature is expressed as tooth marks that flare out from the saw mark. The feature creates a broad V that points towards the kerf. Kerf flare results from side to side movement of the saw as it enters the bone. Kerf flare is recorded as **M**arked when it is present on the marked surface of the bone, **U**nmarked when it is present on the unmarked surface of the bone, and **A**bsent when it is absent.

Trough Morphology and Tooth Width and Trough (Kerf) Width

Saw tooth width can be identified through two methods: measurement of floor patterns; and, measurement of residual tooth trough.

Tooth floor patterns present as islands of bone or parallel grooves in the kerf floor. When a series of islands are present in the kerf floor, the maximum breadth of each island is measured. The maximum breadth of the kerf is measured at the level of the island width measurement. The tooth width is calculated by subtracting the island width from the kerf width and then dividing by two. These measurements are taken for each complete island within the kerf floor.

When parallel tooth grooves are found in the kerf floor, the maximum width of each groove is measured perpendicular to the orientation of the kerf. The complete kerf floor width is measured and recorded as well.

The morphology of the kerf floor as well as the maximum tooth width, maximum island width and maximum kerf width are recorded. The morphology of the kerf floor is recorded as **I**sland, **U**ndulating, or **F**lat.

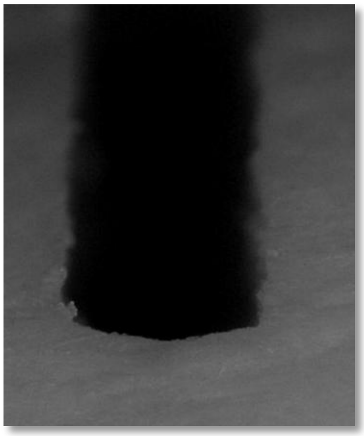
Floor Dips

Floor dips are undulations observed in the tooth grooves when the kerf is viewed in the normal plane. The features are created when the saw is interrupted in the cutting stroke. Floor dips can be measured in false starts and break-away spurs and represent the distance between teeth.

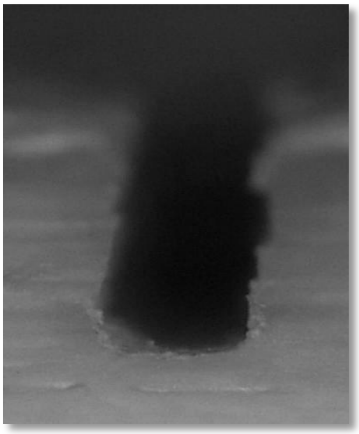
Measure a floor dip from peak to peak. Each complete tooth imprint (definable start and finish) is measured.

Kerf Floor Shape

The kerf floor shape is observed by looking at the false start kerf floor from the side of the test mark (perpendicular to the normal plane). The kerf floor shape is recorded as W-shaped, flat or rounded. A W-shaped kerf floor has a residual island of bone at or near the middle of the kerf floor. A flat kerf floor has 90° angles at one or both floor corners. A rounded kerf floor has rounded floor corners at both corners. If kerf flare is absent, then the feature is observed on marked side. If kerf flare is present, then the opposite side of the test mark is observed.



Flat

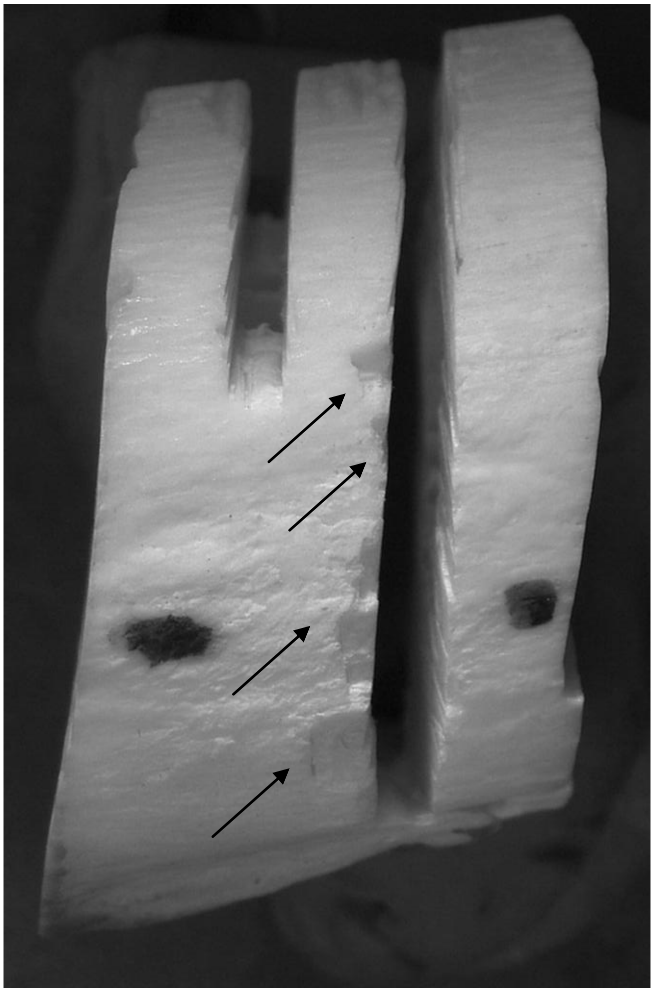


Rounded

W-Shaped

Saw Mark Exit Chippings*

Exit chippings are present along the outer edge of the saw mark and are observed as a small chips displaced from the surface of the bone. To recognize exit chippings, the outer edge of the saw mark is viewed along the perimeter (perpendicular to the cut surface). The edges of opposing cut surfaces of the complete saw cut are examined together for this variable.



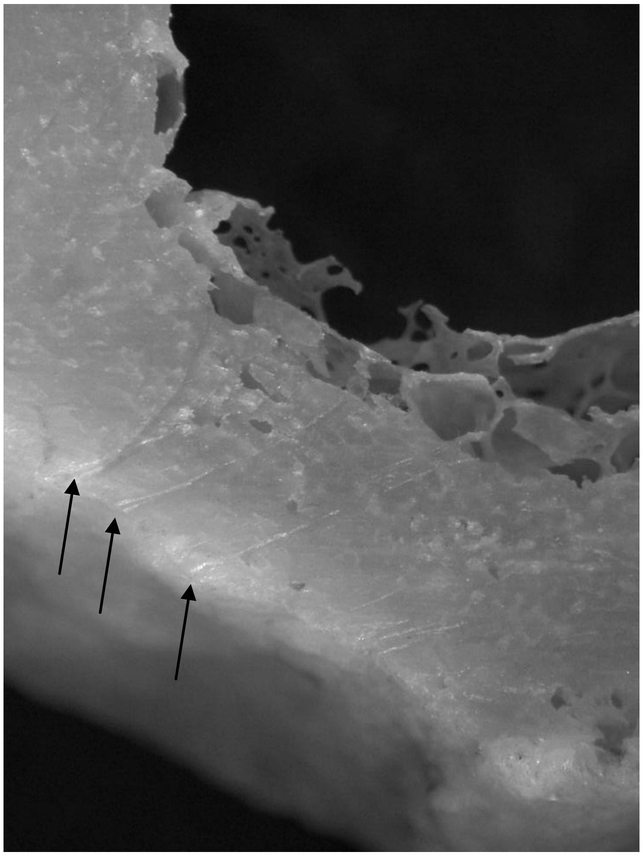
Saw Mark Entrance Shavings*

Entrance shavings are present along the outer edge of the saw mark and are observed as a polished or scalloped surface. To recognize the entrance shavings, the outer edge of the saw mark is viewed along the perimeter (perpendicular to the cut surface). The edges of opposing cut surfaces of the complete saw cut are examined together for this variable.

Pullout Striations (Tooth Scratch) +

Pullout striations are striations that run perpendicular to the patterned striations on the cut surface of the bone. These are created when the saw is withdrawn from the kerf in mid-stroke.

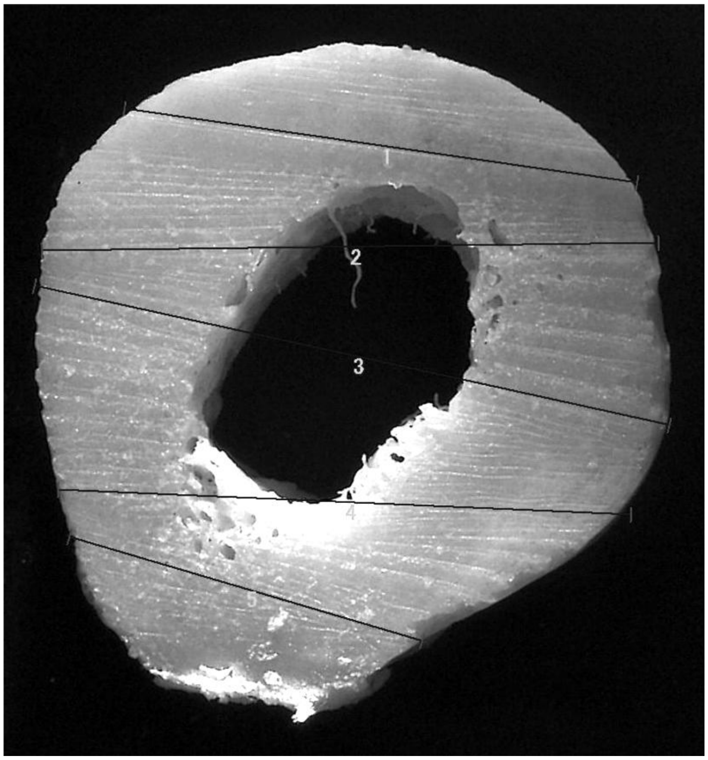
The number of pullout striations is recorded and the distances between each striation is measured and recorded.



Consistency of Cut[+]

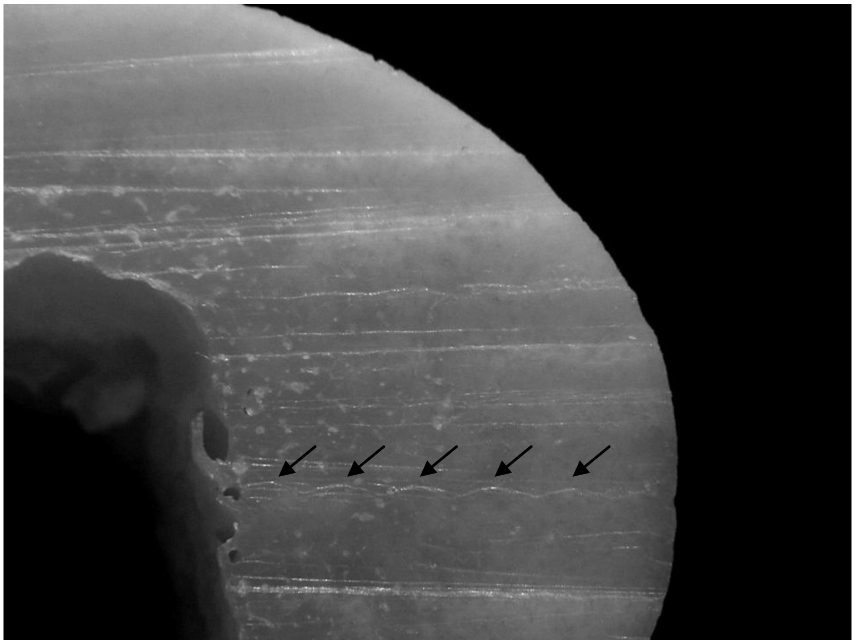
Consistency of the cut is an indication of the saw powered source, manually or mechanically. Mechanically powered saws are expected to produce a saw cut with uniformed expression of striations. A manually powered saw generates a saw mark with erratic striations.

The number of directional changes observed along the cut surface is counted and recorded. When no directional changes are observed (i.e. all striations observed in the cut surface are parallel) the number of directional changes is recorded as 0.



Tooth Hop$^+$

Tooth hop are peaks and valleys observed in a striation. Tooth hop is created when each successive tooth strikes the bone as it enters the kerf and causes movement of the whole blade. The distance from peak to peak or dip to dip of each wave is correlated to the distance between the teeth of the saw. Tooth hop is measured in millimeters.



Harmonics$^+$

Saw mark harmonics are described as peaks and valleys exhibited three-dimensionally in bone cross section. Harmonic oscillations are found to exist in cut marks made with blades of alternating set teeth, and are the direct result of normal cutting action in hand and electrically powered saws. Harmonics are simply the expression of blade drift and are indicators of blade set and TPI.

Harmonics are recorded as present or absent. When present, the inter-harmonic distance is measured approximately 1-2mm above the break-away spur or exit point of the saw (directly opposite the midpoint of the false start kerf). The measurement is taken from the peak of one harmonic to the peak of the neighboring harmonic. A harmonic is differentiated from pullout striations based on the 3-dimensional relief of the feature. Inter-harmonic distance for each neighboring harmonic is recorded.

*Each specimen is marked with an ink dot. The variable is recorded as **M** when observed on the marked surface, **U** when observed on the unmarked surface, and **A** when the variable is absent.

[+] These variables are recorded on cut surface that abuts false start only. The opposing cut surface is not examined.