ABSTRACT

Criminal dismemberment is most commonly committed with a variety of hand-powered saws. These saws leave characteristic marks upon the bone that can assist in the identification of the weapon utilized. The current study provides frequencies of presentation of ten cut surface characteristics and examines intra- and interindividual variation between three hand-powered reciprocating saws. Pig radii were used as a proxy for human remains. 42 cut surfaces were created with three hand-powered reciprocating saws by the same researcher. Cut surface characteristics were assessed macroscopically, microscopically and with Scanning Electron Microscope (SEM), as well as photographed with Reflectance Transformation Imaging (RTI). Cut surface polish is the only characteristic that demonstrates consistently significant difference between saws. Five characteristics demonstrate some variation between blades: entrance shaving, breakaway spurs, breakaway notches, pull-out striae and tooth hop. Four characteristics demonstrate no difference between blades: cut surface striation shape, cut surface striation regularity, harmonics and exit chipping. Tooth hop was the most reliable characteristic for differentiating between blades in this study, while pull-out striae demonstrated high intra-individual variability and a low frequency of presentation making it unreliable for differentiating between saw types. Cut surface striations, exit chipping and breakaway spurs occurred with the highest frequencies and were reliable for determining direction of blade progress and blade stroke, but were not reliable for differentiating between saw blades. Harmonics were absent. Further research is necessary to create large databases of known saw mark examples with known intra- and interindividual variability rates and error rates.

KEYWORDS

Forensic anthropology; Saw mark analysis; Trauma analysis; Dismemberment; Cut surface characteristics; Hand-powered saws

HIGHLIGHTS

- Assists in accumulation of experimental evidence regarding the differentiation of saw blades.
- Results demonstrate both intra- and interindividual variability between blade types.
- Results suggest a minimal number of cut surface characteristics are reliable for distinguishing between blades.
- Levels of intra-individual variability lessen diagnostic ability.
- Low frequencies lessen diagnostic ability.

Dismemberment of a human body refers to the amputation, or partial amputation, of singular or multiple limbs, and may occur pre-, peri-, or post-mortem (1,2). While dismemberment during life may occur accidentally or for medical reasons, criminal dismemberment usually occurs around or after the time of death (2). Previous research into criminal dismemberment has identified the main motives behind dismemberment as an attempt to avoid positive identification of the remains, facilitate ease of transport, or to disfigure or dehumanize the remains (1,3). Criminal dismemberment may be committed with either a knife, axe, saw, or a combination of these weapons (4–6). Furthermore, the perpetrator may try out multiple household weapons, or purchase tools at a local hardware store to facilitate dismemberment (3,4,7). Previous publications have described saws as the most common tool utilized in cases of dismemberment due to their easily accessible nature and designated purpose of sawing through hard materials (4–6).

Previous research has proven that hand-powered saws leave a number of identifiable marks that can identify the class of saw utilized in cases of human dismemberment (5,6,8–10). Class characteristics indicate a specific tool type, such as knife or saw, while individual characteristics focus on differentiating a specific individual weapon (11). Forensic investigators are focused on identifying these characteristic marks left on the bone which can assist in determining the sequence of bodily dismemberment and narrow the field of potential weapons (4,10,12). These assessable saw mark characteristics are created due to differences in blade morphology, namely tooth size, set and shape (1,5,8,13). Unlike mechanical saws, hand-powered saws are characterised by solely requiring the power of a human operator to function which can result in presentation variability of saw mark characteristics (1,14). Characteristics that have previously been noted to occur on kerf walls and fully sectioned cut surfaces due to the reciprocating action of hand-held saws are presented in Table 1. There are a number of other characteristics which can only be assessed on incomplete kerfs and kerf floors that are not discussed here, as they are outside the scope of the current study.

In recent years, toolmark analysis has been challenged as lacking specific, standardised protocols for analysis and training, lacking both reliability and repeatability testing, and relying on a limited scientific knowledge base that is the result of experiential, rather than experimental, knowledge (15,16). In response to such criticisms, researchers have become focused on assessing the applicability of saw mark analysis and providing predicted error rates surrounding saw mark characteristics (1,5,11,13,17,18). Although research concurs on the usefulness of false start kerf width and shape (13,17), the research surrounding the variability of cut surface characteristics (pull-out striae, tooth hop, harmonics and entrance shaving) remains inconclusive. Both Bailey *et al*. (17) and Noguiera *et al*. (13) assess only characteristics seen with false start kerfs. Bailey *et al*. (17) found that 70-90% of the time saws could be eliminated based on kerf width alone. Noguiera *et al*. (13) confirmed the utility of kerf width, with accuracy between 70-90%, also finding that kerf profile and shape could be used in combination to exclude saws. Love *et al.* (18) found that kerf width, floor shape, wall shape and average tooth hop were important variables when discriminating between saws, with an accuracy between 83-91%. Trough morphology, kerf flare, pull-out striae, entrance shaving, and harmonics were too infrequently noted to be evaluated. Berger *et al*. (1) also found kerf width and shape to be significant in differentiating between blades, in addition to cut surface drift, harmonics, size of exit chipping and striation regularity. Pull-out striae, tooth hop, entrance shaving, and kerf flare were excluded from their statistical analysis due to either the limited number of instances in their sample, or similar prevalence between blades.

This is inconsistent with Love *et al.* (18) who found harmonics too infrequent to be useful, and tooth hop to be an important indicator between blades. Symes *et al.* (5,9) state that harmonics are present in almost all alternating blade sets, however Berger *et al.* (1) noted harmonics in both wavy and alternating blade sets, while Love *et al.* (18) did not note any. Tooth hop is similarly contested, with pull-out striae and entrance shaving not present in large enough quantities to be useful. Experimental research that has focused solely on cut surface characteristics (10,14,19) has been focused on use-wear patterns or visibility post-incineration. This brief overview of the experimental literature highlights the variable nature of experimental results pertaining to saw mark analysis. Love (11) also highlights the fact that there is yet to exist a method that provides appropriate guidance with regards to the most useful characteristics

The current study will focus solely on the presentation of cut surface characteristics and assess the intra-individual and interindividual variation between three saws. Intra-individual variation refers to the variation between cut surfaces created with the same saw, while interindividual variation refers to the variation between cut surfaces created with different saws (18). The current study examines the presentation of cut surface features on experimentally sectioned bone surfaces cut by three hand-powered reciprocating saw blades to provide frequencies of occurrence of cut surface characteristics and assess intra- and interindividual variation between the three saws. This study is not meant to be an all-encompassing examination of the variability and reliability of cut surface characteristics between all hand-powered blades, as such, the results are applicable to the three saws utilized and may not be representative of similar saw classes.

Materials and Methods

Materials

Eleven defleshed juvenile pig (*Sus scrofa domestica*) radii were utilised for this study. Pig was chosen as a proxy for human bone as it is commonly used in experimental skeletal trauma analysis and has been proven to be of similar hardness to human cortical bone (6,10,17,20–26). Fleshed pig knuckles were purchased from Mckanna Meats, London, U.K., where the animals had been butchered the same day for consumption. No animals were slaughtered for the purposes of this experiment. All specimens were macerated on the same day of purchase in the UCL Bioarchaeology Laboratory utilizing manual de-fleshing and hot water enzyme maceration (27,28). In an attempt to enhance experimental replicability (29) specimens were macerated prior to sectioning. Defleshed porcine bones have previously been used in tool mark analysis research (13,21,30). While macerating post-sectioning would have been more realistic, maceration was completed pre-sectioning to maintain a controlled experimental environment and not result in accidental damage to the cut surfaces during de-fleshing and maceration.

Three new, hand-powered saws were used for this experiment (Table 2; Fig. 1); these saws were selected to represent a range of measurable variables, including tooth shape, tooth set, power stroke and teeth per inch (TPI), and because they are readily available for purchase in hardware stores (2,9). New hand-powered saws were utilized to prevent cut surface characteristics from becoming altered due to tooth blunting from previous use (14).

Cutting Method

The proximal and distal epiphyses were removed from each specimen, so that all saw cuts were made solely through the cortical bone of the diaphysis ensuring the retention of saw marks (4,6).

Two bench vices (Irwin TV150 Woodcraft Vice) with 20mm thick padding attached to the jaws were set with the diaphyseal bone segment held between them. Two bisecting cuts were made through each diaphyseal segment. A backstroke was made at the intended sawing location to avoid creating unnecessary false start kerfs and striae. The saw was held perpendicular to the long axis of the bone for the entirety of each cut, minimizing the creation of directional changes. Upon cut completion the saw was then removed from the bone in a single upward stroke, facilitating the creation of pull-out striae. To maintain regularity of force, each cut was made manually by the same right-handed female researcher. A digital metronome (the Metronome, by Soundbrenner application for Apple iPhone 6s) was utilized to control the pace of saw motion. A speed of 60 beats per minute (BPM) was chosen (23), with the power stroke occurring on each beat, until the bone was completely sectioned. Seven cuts were made with each saw, resulting in 14 cut surfaces per saw and 42 cut surfaces in total.

Analysis

The resulting cut surfaces were examined using a Dino-Lite Pro HR Digital Microscope (AM7000/AD7000 Series) set at 10X magnification with oblique lighting, following recommendations for the microscopic assessment of saw mark characteristics (5,9,31), followed by macroscopic assessment. Specimens were subsequently assessed using a Zeiss EVO 25 SEM set in VP mode at 15X-18X magnification with micrographs taken in succession, overlapping images slightly so that they could be easily re-aligned in Adobe Photoshop (CC 2018) (14) and photographed with Reflectance Transformation Imaging (RTI) software for ease of presentation of cut surface features (32). Ten cut surface features were assessed in this study (Table 1), chosen due to their discussion in previous literature, with definitions derived from multiple sources for enhanced clarity (1,5). Characteristics were: (i) scored as either present or absent; (ii) documented by location of occurrence; and (iii) measured to the nearest tenth of a millimetre, if applicable. For the purposes of this experiment each side of the cut surface was given an arbitrary letter (A-D), used to indicate side of the cut surface during analysis and final determination of direction of blade progress and blade stroke. This was done in lieu of recording the characteristics based on anatomical position as would be done in human dismemberment cases (5). Following previous research (1,5,8) blade progress was determined based on presence and direction of striations, which are perpendicular to blade progress, and the location of breakaway spurs or notches. Blade stroke was also determined based on the presence and direction of striations, which are parallel to blade stroke, and the presence of exit chipping and entrance shaving.

Statistical Analysis

Pearson's chi-square was completed to determine if the variation of frequency of each characteristic between each saw was of significant difference. Analysis was separated by imaging method to ensure that results were not tainted due to variation across recording methods. Analysis was completed in SPSS. P-values of ≤ 0.05 were considered to illustrate statistically significant difference.

Results

The maximum prevalence of characteristics recorded on each saw is detailed in Table 3. Frequency was further divided by recording method (Table 4), demonstrating that some variation also exists between recording method utilized for assessing cut surface characteristics. While the majority of cut surface characteristics could be visualized accurately with all recording methods variation existed due to differences in magnification capacity. Notably, macroscopic assessment incorrectly assessed three instances of cut surface striations cut by the junior hacksaw as uniform although microscopic and SEM assessment correctly identified them as non-uniform. Due to the enhanced magnification of SEM, surface features were occasionally obstructed by the underlying bone morphology making characteristic analysis impossible and resulting in an over-estimation of cut surface polish compared to the other methods. Similarly, SEM was able to identify a greater number of tooth hop and pull-out striae than the other two techniques.

Tables 5 through 7 present the results of statistical analysis. No differences were observed, in any imaging modality, for the following traits: cut surface striations, striation regularity, exit chipping and harmonics. Cut surface polish was the only characteristic to consistently demonstrate significant differences between saws. Cut surface striations, exit chipping, and breakaway spurs and notches presented with the highest frequencies throughout the entire sample. Harmonics was the only absent characteristic. Presence and direction of striations, and presence of exit chipping and entrance shaving enabled direction of blade stroke to be accurately assessed 80.9% (34/42) of the time while the presence and direction of striations, and presence of breakaway spurs and/or notches enabled direction of blade progress to be accurately assessed 85.7% (36/42) of the time.

Cut Surface Striations and Regularity

Cut surface striation pattern and uniformity demonstrate no differences due to saw. Striations were recorded as straight and non-uniform 100% of the time on cuts made by each blade. Striations were noted to be closer together in specimens cut by the junior hacksaw, the blade with the largest TPI.

Cut Surface Polish

Cut surface polish was recorded most frequently on cuts made by the handsaw, with a maximum prevalence of 92.9% (13/14). Cuts made by the tenon saw were only recorded as having a maximum prevalence of 28.6% (4/14), while cuts made with the junior hacksaw had a maximum prevalence of 21.4% (3/14).

Entrance Shaving

Entrance shaving was only recorded on cuts made by the handsaw with a frequency of 57.1% (8/14). Of these, 87.5% (7/8) were present on the entrance side of the cut surface.

Exit Chipping

Exit chipping was recorded on 100% (42/42) of the specimens, presenting with no difference in prevalence between blades. The junior hacksaw was the only blade to create exit chipping on both the entrance and exit sides of the cut surface on 71.4% (10/14) of the specimens (Fig. 2).

Breakaway Spurs and Notches

Breakaway spurs and notches present with slight differences between saws; breakaway spurs decreased in frequency from the handsaw (100%; 14/14) to the tenon saw (85.7%; 12/14), and again from the tenon saw to the junior hacksaw (78.6%; 11/14), while breakaway notches occurred with the same frequency from the handsaw and tenon saw (14.3%; 2/14), but increased in cuts made by the junior hacksaw (35.7%; 5/14), however notches generally occurred with less frequency than spurs. Both breakaway spurs and notches were 100% accurate in determining direction of blade progress when present.

Tooth Hop

Tooth hop occurs most frequently on cuts made with the tenon saw (71.4%) and demonstrates clear distinction in size between saw blades. Fig. 3 illustrates the clear distinction of tooth hop measurements between blades, also demonstrating slightly greater intra-individual variation within cuts made by the tenon saw (a difference of up to 2.53mm). Figs. 4 and 5 illustrate two different instances of tooth hop created by the tenon saw, one of which measures 3.5mm (Fig. 4), the other measures 1.6mm (Fig. 5). Both cut surfaces are corresponding, meaning that they are opposite sides of the same sectioning cut. The average tooth hop measurement of each saw slightly overestimates the actual distance between teeth; cuts made with the handsaw overestimate the distance between teeth by 0.38mm, with an average measurement of 3.88mm, cuts made with the tenon saw overestimate the distance between teeth by 0.65mm, with an average measurement of 2.15mm, and cuts made with the junior hacksaw overestimate the distance between teeth by 0.3mm, with an average measurement of 0.8mm.

Pull-out Striae

Pull-out striae occurred most frequently on cuts made with the tenon saw (42.9%) and demonstrates distinction in size between saw blades. An example of pull-out striae recorded in this experiment can be seen in Fig. 6. The average measurement of this specimen is 3.45mm, while the actual distance (AD) between teeth of the tenon saw is 1.5mm. In this instance the pull-out striae are representative of the distance between three, rather than two teeth, due to the alternating set of the teeth. Pull-out striae measurements from cuts made with the junior hacksaw averaged 0.6mm, representative of the distance between two teeth (AD 0.5mm). Fig. 7 illustrates the distinction of pull-out striae measurements between the three saws utilised in this experiment, as well as the high level of intra-individual variability seen in cuts made by the tenon saw. There is a measurement overlap present between the handsaw and the tenon saw, however there is only one measurement of pull-out striae available from the handsaw. Measurements would be expected to group together around the AD of the pull-out striae, however Fig. 7 illustrates the presence of an outlier value which suggests higher variability of pull-out striae presentation within cuts made by the tenon saw.

Discussion

The results of the current study demonstrate the presence of both intra- and interindividual variation between the three hand-powered reciprocating saws utilized in this study. Four characteristics demonstrate no difference between blades: cut surface striation shape, cut surface striation regularity, harmonics and exit chipping. All blades produced straight, non-uniform striation patterns conforming to traditional knowledge of reciprocating, hand-powered saws (9). Three instances of 'uniform' striations were noted during macroscopic analysis, however this is due to the lack of appropriate magnification to assess the minute kerf wall striations created by the junior hacksaw. Of note, was the difference in distance between each striation with the blade with the largest TPI (the junior hacksaw) having striations noticeably closer together and more regular in spacing. This observation may suggest a correlation between striation width and TPI that could be useful in determining between blade types with further study, however the results of this study suggest that the presence of straight, non-uniform striations alone is not useful for differentiating between hand-powered, reciprocating blades. Harmonics were not recorded on any of the specimens, an occurrence similarly noted by Love *et al.* (18). This suggests that harmonics are an unreliable characteristic to assess tooth set between hand-powered, reciprocating blades. Previous researchers have demonstrated the utility of harmonics, attributing harmonics to almost all alternating set blades (1,5), although this was not demonstrated in this study. Further research surrounding the cause and presentation of harmonics should be undertaken. Exit chipping presented with 100% frequency, demonstrating no difference between blades. However, the location of exit chipping demonstrates a previously unreported problem with determining the direction of blade stroke of pull-stroke saws. While 100% of specimens cut with the handsaw and the tenon saw (push-stroke blades) were accurately assessed for blade stroke, only 21.4% of specimens cut by the junior hacksaw (a pull-stroke blade) were accurately assessed. This is because the junior hacksaw produced cut surfaces with exit chipping of similar size on both the entrance and exit sides of the cut surface, where it would be expected for exit chipping only to occur on the entrance side of the cut surface due to the cutting action occurring during the pull stroke. This suggests that the force exerted by the experimenter may have overpowered the saw blade morphology to create exit chipping during both the cutting and the passive stroke of the sawing action, thus resulting in exit chipping on both entrance and exit sides of the cut surface. The lack of reliability surrounding the presence of exit chipping and determination of blade stroke direction on cuts made with a pull-stroke blade has not previously been mentioned in the literature and should be further examined in the future. Exit chipping can be used to assist in determining directionality of dismemberment but is not useful for differentiating between hand-powered saw blades.

Cut surface polish is the only characteristic that demonstrates consistently significant difference between saws, presenting most frequently in cuts made by the handsaw (92.9%), an alternating blade, and least frequently in cuts made by the junior hacksaw (21.4%), a wavy blade. Cut surface polish is most commonly attributed to saw power, with greater speed and power creating more polish (1,5), however has also been attributed to a wavy set blade rubbing against the bone surface (9), and the blade bending or binding in the kerf (1,5). In the current study, saw power was similar between blades, suggesting that cut surface polish in this case is caused by blade bending and extended contact of the larger bladed handsaw in the kerf during sawing. Although cut surface polish shows some variation between blades, the variability of potential causes makes cut surface polish unreliable when distinguishing between saws of similar power.

Five characteristics demonstrate some variation between blades: entrance shaving, breakaway spurs, breakaway notches, pull-out striae and tooth hop. Entrance shaving demonstrated significant difference between saw blades when assessed macroscopically and microscopically, however only occurred on cuts made by the handsaw (57.1%). This suggests that entrance shaving may indicate a difference in blade morphology, possibly as a result of the blade bending in the kerf during sawing, however does not provide utility for differentiating between the blades in this study. Nonetheless, when present, entrance shaving is accurate 81.8% of the time for determining direction of blade stroke, demonstrating reliability when determining directionality. Entrance shaving can be used to assist in determining directionality of dismemberment but are not useful for differentiating between hand-powered saw blades. Breakaway spurs and notches demonstrate some variation between saws and are consistently reliable when used to assess direction of blade progress. In the current study, breakaway spurs did not occur as large boney projections but rather as small chipping and flaking more akin to exit chipping but located at the terminal end of the cut. This is unsurprising as previous research has demonstrated that the size of the spur is dependent upon the force applied to the bone and may be more common in handheld power saws (5). Furthermore, the experimental protocol taken in the current study held both ends of the diaphyseal segment in place during sectioning, stopping the sawyer from being able to break the bone with physical force at the terminal end of the cut resulting in a lack of large boney projections. In this study breakaway spurs occurred most frequently on cuts made by blades with lower TPI, and breakaway notches occurred most frequently on blades with a larger TPI. Similarly to cut surface polish, breakaway spurs and notches have been attributed to the amount of force and leverage applied during sawing (6). Although the force applied during sawing was similar between saws, the longer saw blades with a lower TPI may have produced greater leverage across the bone during sawing, thus producing more breakaway spurs. Breakaway notches, however, do not conform to this conclusion, occurring most frequently in this study due to the smallest of the blades with the largest TPI. Although not useful in the current study to distinguish between hand-powered reciprocating blades both breakaway spurs and notches were 100% accurate when determining directionality of blade progress. Accurately determining directionality of blade progress and stroke can assist in determining perpetrator preference, progression of dismemberment, and placement of the body during dismemberment (12).

While the presence alone of pull-out striae and tooth hop does not indicate a significant difference between saws, metric assessment suggests that these two characteristics can be used to differentiate between saws in the current study. Metric assessment was completed on all observed instances of tooth hop and pull-out striae. Tooth hop is created by blade movement as it cuts through the bone, leaving an indication of the distance between saw teeth (5). Love *et al.* (18) noted tooth hop to be an important characteristic when classifying saw type, although Berger *et al.* (1) found it presented too infrequently to analyze in their study. The results of the current study suggest that average tooth hop measurements are reliable for distinguishing between hand-powered blades. Metric assessment demonstrates that tooth hop is distinct between all blades, representative of the different TPIs and of the distance between two teeth. In contrast, pull-out striae demonstrate some distinction between blades, however, are far more variable and occur with less frequency than tooth hop. Pull-out striae only occurred on one specimen cut by the handsaw. This low frequency makes it difficult to draw conclusions surrounding the presentation of pull-out striae due to the handsaw. Pull-out striae seen on specimens cut with the tenon saw, an alternating blade, appear to correspond to the distance between three teeth, rather than the distance between two teeth, while pull-out striae from the junior hacksaw, a wavy blade, correspond to the distance between two teeth. This correlates well with the previous research (5) suggesting that alternating blades will produce pull-out striae corresponding to the distance between three, rather than two teeth, as every other tooth is bent to the opposing side of the blade. Possibility for error is thus greater when utilizing measurements of pull-out striae if tooth set is unknown at the time of assessment. Pull-out striae should be used in conjunction with other characteristics, when possible, to substantiate an assessment, rather than utilized as the sole proof of an assessment (5), and the variability of pull-out striae size within a single blade type necessitates caution, should only one measurement be available. Average measurements of both tooth hop and pull-out striae slightly overestimated the distance between teeth, with an overestimation of tooth hop between 0.2-0.7mm, and an overestimation of pull-out striae between 0.1-0.4mm, upon removal of the outlier value which underestimates the distance between two teeth, (supposing that pull-out striae represent the distance between three alternating teeth and two wavy set teeth). This propensity to exaggerate tooth size should be considered when assessing cut surface characteristics, as an inaccurate TPI assessment could be generated from an exaggerated measurement. Cuts made by the tenon saw demonstrate the largest occurrence of both tooth hop and pull-out striae, but also the greatest intra-individual variability of measurements. Pull-out striae measurements from the tenon saw range from 3.1-3.65mm, with an outlier of 1.3mm, while tooth hop measurements range from 1.0-3.53mm. Figs. 4 and 5 illustrate both cut surfaces produced during a single transecting cut made by the tenon saw, demonstrating the variation in measurement of tooth hop that can occur within a single cut and how two sides of the same cut can offer different information if assessed separately. This intra-individual variability could be due to the tooth shape (the tenon saw is the only universal tooth blade in this experiment), or due to the greater number of characteristics present in specimens cut with the tenon saw, potentially resulting in a higher level of variability compared to the other saws. Although both tooth hop and pull-out striae presented with some differences between the three saws utilized in this experiment, the amount of intra-individual variation seen, especially in the tenon saw, along with the low frequency of presentation suggests a higher chance of error when less measurements are available.

While some characteristics illustrate interindividual variability between saws, there also exists intra-individual variability within each individual saw. Intra-individual variability was seen most often in the tenon saw, with the universal tooth set, specifically noted in measurements of tooth hop and pull-out striae. The low frequency of presentation of many of the cut surface characteristics analyzed in this study, such as pull-out striae, tooth hop and harmonics, confirms the high variability of cut surface characteristic presentation. Although a characteristic such as tooth hop may be useful for differentiating between blade types, the low frequency of presentation means that tooth hop has a low chance of being present upon the bone surface in a case of criminal dismemberment. Those characteristics which present with the highest frequencies, such as striations, breakaway spurs, and exit chipping, did not demonstrate interindividual variation in the current study, however are highly reliable for assessing directionality of blade stroke and progression.

There are several limitations to this study. First, although previous research has often utilized pig bone as a proxy for human remains, inherent differences may still exist resulting in potential differences between how saw marks will show up on human versus pig bone (13,21,26). Second, the choice to macerate the bones prior to cutting maintained experimental control and ensured that no marks were made post-sawing nor that fragile chipping around the edges of the cut surface were lost, however does not replicate a real world dismemberment scenario where dismemberment is carried out on fleshed human remains . Third, the current study uses only three saws so is not an exhaustive look at all types of hand-powered saw blades. There are a large variety of hand-powered saws available and this study should be considered an initial examination of the frequency and variability of presentation of cut surface characteristics, rather than an exhaustive examination of all possible hand-powered saw blades. Furthermore, the small sample size may have resulted in a low frequency of presentation, suggesting that large sample sizes should be utilized for further statistical analysis in the future. Further research may assist in gathering additional experimental data and creating estimates on the reliability and predictive value of each cut surface characteristic to determine saw type.

Conclusion

The current study has demonstrated that cut surface characteristics can demonstrate interindividual variation between reciprocating hand-powered saw blades, however these characteristics can also present with high intra-individual variation and low frequencies that may lower their diagnostic abilities. Four characteristics demonstrated no difference between blades: cut surface shape, cut surface striation pattern, harmonics and exit chipping. One characteristic demonstrated consistently significant difference between blades: cut surface polish. Five characteristics demonstrated some difference between blades: breakaway spurs and notches, entrance shaving, pull-out striae and tooth hop. While tooth hop, pull-out striae, entrance shaving and cut surface polish presented with differences between saws they occurred at low frequencies throughout the entire sample and tooth hop and pull-out striae, in particular, demonstrated intra-individual variation, most notably in cuts made by the tenon saw. Other cut surface characteristics presented with high frequency, such as breakaway spurs and exit chipping, but did not assist with the differentiation of saw type in this study. The current study has also demonstrated the contested nature of harmonics, and the possible difficulties associated with correlating exit chipping to the direction of blade stroke of pull-stroke blades. Ideally characteristics would be used in conjunction with each other, however due to the low level of frequency of presentation of certain characteristics there may be a minimal number of characteristics to utilize for assessment in a medico-legal scenario. In such cases having reliable rates of frequency and accuracy is critical. Within the field of saw mark analysis, and the wider forensic science community as a whole, there exists a lack of standardised methodology based on sound experimental research, a lack of known error rates and a lack of understanding of the amount of variation present (15,16). Saw mark analysis must continue to be examined from an experimental standpoint, creating accurate, reliable and repeatable conclusions and protocols for practitioners to utilize for both training and practice. Further research must be completed on a wide selection of known blades with a focus on creating known intra- and interindividual variability and error rates that can be used in a practical forensic setting for saw class identification.

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Tables

TABLE 1 – A *table describing each characteristic assessed in this paper, definitions derived from Symes et al.* (5) *and Berger et al.* (1).

Definitions of Saw Mark Characteristics	
Cut Surface Striations	Lines left by the saw upon the bone section that indicate direction of blade progress. Striations are either straight or curved.
Striation Regularity	Number of directional changes and uniformity of cut surface striations. Uniform striations are parallel, consistent, and evenly spaced, with no directional changes. Non-uniform striations can be non-parallel, variable in spacing, and may have directional changes.
Cut Surface Polish	Polishing of the cut surface due to extended contact of the blade during sawing. This is visualised as 'eburnation' across the surface of the sectioned long bone, with no visible striations remaining. Commonly attributed to high-powered saws.
Pull-out Striae	Scratches that run perpendicular to cut surface striations, indicating that the saw was withdrawn from the kerf mid-stroke.
Tooth Hop	Distance between waves in cut surface striations caused by blade movement as it enters the kerf, indicating distance between teeth.
Harmonics	Three-dimensional peaks and valleys that are oblique to both the cutting stroke and direction of blade progress. Indicating distance between teeth.
Breakaway Spur	A projection of un-cut bone at the terminal end of the bone section, due to force breaking the remaining bone tissue. The size of the spur is dependent upon the amount of force applied to the bone. Large amounts of force may fracture the bone. Indicates terminal end of cut.
Breakaway Notch	A segment of missing bone at the terminal end of the bone section. This will correspond with the spur in an adjacent bone section. Indicates terminal end of cut.
Entrance Shaving	As the saw blade enters the bone it may shave the entrance, leaving a polished or scalloped appearance. Indicates the entrance stroke.
Exit Chipping	Bone chips and flaking occurring at the end of the cutting stroke. Indicates the exit stroke.

TABLE 2 – A *table describing the three hand-powered saws utilized in this experiment.*

	Saw Type		
	Handsaw	Tenon Saw	Junior Hacksaw
Purpose	Wood	Wood	Metal
Tooth Shape	Rip	Universal	Rip
Tooth Set	Alternating	Alternating	Wavy
Distance Between Teeth	3.5mm	1.5mm	0.5mm
*TPI**	7	15	32
Power Stroke	Push	Push	Pull

*Teeth per inch, as per the saw manufacturer. There are 25.4mm in an inch.

TABLE 3 – *A table detailing the number and percentage of each characteristic recorded, by saw.*

	Saw Type					
	Handsaw		Tenon Saw		Junior Hacksaw	
Cut Surface Striations						
Straight	14	100%	14	100%	14	100%
Curved	0	-	0	-	0	-
Striation Regularity						
Non-Uniform	14	100%	14	100%	14	100%
Uniform	0	-	0	-	0	-
Cut Surface Polish						
Present	13	92.9%	4	28.6%	3	21.4%
Absent	1	7.1%	10	71.4%	11	78.6%
Pull-out Striae						
Present	1	7.1%	6	42.9%	3	21.4%
Absent	13	92.%	8	57.1%	11	78.6%
Tooth Hop						
Present	2	14.3%	10	71.4%	2	14.3%
Absent	12	85.7%	4	28.6%	12	85.7%
Harmonics						
Present	0	-	0	-	0	-
Absent	14	100%	14	100%	14	100%
Breakaway Spur						
Present	14	100%	12	85.7%	11	78.6%
Absent	0	0%	2	14.3%	3	21.4%
Breakaway Notch						
Present	2	14.3%	2	14.3%	5	35.7%
Absent	12	85.7%	12	85.7%	9	64.3%
Entrance Shaving						
Present	8	57.1%	0	-	0	-
Absent	6	42.9%	14	100%	14	100%
Exit Chipping						
Present	14	100%	14	100%	14	100%
Absent	0	-	0	-	0	-

TABLE 4 – *Frequency of cut surface characteristic, by imaging method.*

	Imaging Method		
	Macroscopic	Microscopic	SEM
Cut Surface Striations			
Straight	42	42	42
Curved	0	0	0
Striation Regularity			
Uniform	3	0	0
Non-Uniform	39	42	42
Cut Surface Polish			
Present	12	11	20
Absent	30	31	22
Pull-out Striae			
Present	5	5	9
Absent	37	37	33
Tooth Hop			
Present	5	5	11
Absent	37	37	31
Harmonics			
Present	0	0	0
Absent	42	42	42
Breakaway Spur			
Present	37	31	36
Absent	5	11	6
Breakaway Notch			
Present	6	6	5
Absent	36	36	37
Entrance Shaving			
Present	9	5	0
Absent	33	37	42
Exit Chipping			
Present	42	42	42
Absent	0	0	0

TABLE 5 – *Chi-squared results for SEM assessment.*

	Saw Type					
	Hacksaw	Tenon Saw	Jr Hacksaw	Pearson Chi Square Value	df	Sig
Straight Striations	14	14	14	-	-	-
Non-Uniform Striations	14	14	14	-	-	-
Cut Surface Polish	13	4	3	17.373	2	<0.005
Pull-Out Striae	0	4	1	5.003	2	.052
Tooth Hop	2	6	2	4.200	2	.122
Harmonics	0	0	0	-	-	-
Breakaway Spur	13	12	11	1.167	2	.558
Breakaway Notch	1	1	3	1.816	2	.403
Entrance Shaving	0	0	0	-	-	-
Exit Chipping	14	14	14	-	-	-

TABLE 6 – *Chi-squared results for microscopic assessment.*

	Saw Type					
	Hacksaw	Tenon Saw	Jr Hacksaw	Pearson Chi Square Value	df	Sig
Straight Striations	14	14	14	-	-	-
Non-Uniform Striations	14	14	14	-	-	-
Cut Surface Polish	10	1	0	22.416	2	<0.005
Pull-Out Striae	0	3	1	3.868	2	.145
Tooth Hop	1	3	0	3.868	2	.145
Harmonics	0	0	0	-	-	-
Breakaway Spur	13	8	10	4.680	2	.096
Breakaway Notch	1	2	3	1.167	2	.558
Entrance Shaving	5	0	0	11.351	2	.003
Exit Chipping	14	14	14	-	-	-

TABLE 7 – *Chi-squared results for macroscopic assessment.*

	Saw Type					
	Hacksaw	Tenon Saw	Jr Hacksaw	Pearson Chi Square Value	df	Sig
Straight Striations	14	14	14	-	-	-
Non-Uniform Striations	14	14	11	6.462	2	.040
Cut Surface Polish	10	2	0	19.600	2	<0.005
Pull-Out Striae	1	3	1	1.816	2	.403
Tooth Hop	0	4	0	8.842	2	.012
Harmonics	0	0	0	-	-	-
Breakaway Spur	14	12	11	3.178	2	.204
Breakaway Notch	0	2	4	4.667	2	.097
Entrance Shaving	9	0	0	22.909	2	<0.005
Exit Chipping	14	14	14	-	-	-

Figure Legends

FIG. 1 – *A photograph of the three saws used in this study. A is the Junior Hacksaw, B is the Tenon Saw, and C is the Handsaw.*

FIG. 2 – *An RTI image of a specimen cut with the junior hacksaw demonstrating the occurrence of exit chipping on both the entrance (dashed arrows – side B) and the exit (solid arrows – side D) sides of the cut surface.*

FIG. 3 – *A boxplot demonstrating the tooth hop measurements taken with each analytical method, by saw type. This figure illustrates almost no overlap between saws, demonstrating the clear distinction of tooth hop measurements between the three saws utilized in this experiment and the slightly greater variability within cuts made by the tenon saw. The central line represents the median, while the 'x' represents the mean of the measurements. The bottom line of the box represents the median of the 1st quartile and the top line of the box represents the median of the 3rd quartile, with the whiskers above and below extend to the minimum and maximum values.*

FIG. 4 – *An RTI image of a specimen cut with the tenon saw demonstrating tooth hop (circle), both measuring 3.5mm.*

FIG. 5 – *An RTI image of a specimen cut with the tenon saw demonstrating an instance of tooth hop (circle), measuring 1.6mm.*

FIG. 6 – *An RTI image of a specimen cut with the tenon saw demonstrating two instances of pull-out striae (circles). The average measurement of pull-out striae on this specimen is 3.45mm, although the actual distance between saw teeth is 1.5mm.*

FIG. 7 – *A boxplot demonstrating the pull-out striae measurements taken with each analytical method, by saw type. This figure demonstrates the distinction of pull-out striae measurements between the three saws utilized in this experiment, as well as the higher level of variability within cuts made by the tenon saw. There is some overlap between the handsaw and tenon saw, however only one measurement was available from cuts made with the handsaw. The central line represents the median, while the 'x' represents the mean of the measurements. The bottom line of the box represents the median of the 1st quartile and the top line of the box represents the median of the 3rd quartile, with the whiskers above and below extend to the minimum and maximum values. The blue dots extending beyond the whiskers represent outlier values.*