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ORIGINAL ARTICLE

# Cutting crime: the analysis of the “uniqueness” of saw marks on bone

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**Abstract** Witness marks produced on bone by the use of saws have traditionally been examined using stereomicroscopy. The marks are typically found on the kerf wall or floor and give important information about the implement that made them. This paper describes a new approach to the analysis of witness marks left on kerf walls and floors from crimes involving dismemberment. Previously, two types of marks have been identified: deep furrows formed during the pull stroke and fine striations formed on the push stroke. These types of striation allow the class of saw to be identified, but not an individual saw. With the advent of environmental scanning electron microscopy (ESEM), insulating materials can now be examined without the need for conductive coatings to be applied. This allows materials to be examined at higher magnifications than those available with stereomicroscopy. Here we report on a new, third type of striation that is visible at higher magnifications on ESEM images. These striations are formed from the imperfections on the cutting teeth of saws and give real possibilities of uniquely identifying whether or not a particular saw was used to cause the mark. In blind trials conducted on sawing of nylon 6.6, different individual saws could be successfully identified even if different people used the saw. We discuss ways in which these results can be extended to bone and how this may assist in the investigation of the act of dismemberment.

The authors declare that they have no competing financial interests.

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## Introduction

Postmortem dismemberment is generally conducted using axes, knives, or saws. There are two types of dismemberment that are commonly seen: localized, such as the removal of the head or hands in an attempt to hinder identification of the victim, or generalized at multiple sites (commonly bisection of limbs or disarticulation of the joints) to aid in the disposal of the body [1]. Where saws are used in the dismemberment, characteristic witness marks (tool marks) are left on the bone. The nature of the mark that is left depends on the size, shape, width, and set of teeth and the sawing action of the user. The analysis of saw marks is complex because the saw has multiple cutting teeth and is repeatedly moved to generate the witness mark.

The slit mark made by a saw is referred to as the kerf (Fig. 1). Kerf walls and floors contain important information about the saw that was used [2, 3]. The kerf wall is the vertical part of the cut and consists of a number of deep furrows and fine striations. The deep furrows are formed during the pull stroke of the cutting action when the teeth of the saw blade are all in alignment. Counting the number of deep furrows within the kerf wall thus allows one to attempt to calculate the number of strokes made to cut the material. The fine striations are formed on the forward push stroke when each tooth on the blade enters slightly lower than the previous one. The number of striations correlate to the number of teeth used in the stroke (typically two thirds of the total number of teeth) [4]. Sometimes, vertical marks are left when the blade is removed from a jammed stroke. These vertical marks give a measure of the tooth distance

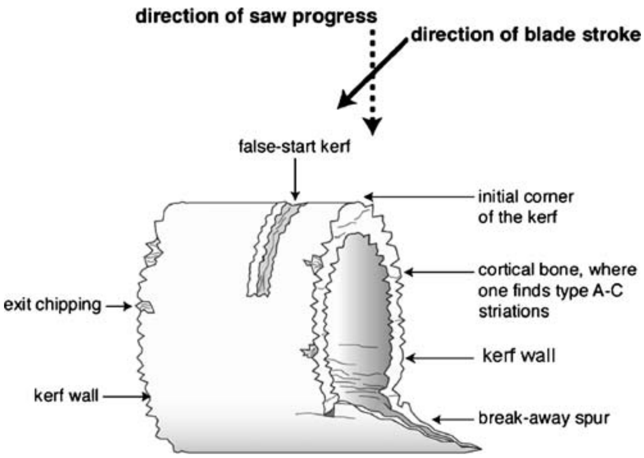


**Fig. 1** The common features of a saw mark on bone

(either between adjacent teeth or a multiple of this). Kerf floors contain information about the points of individual teeth and their relation to each other. Kerf floors are commonly found where a partial cut has been made, or in the spur of bone that is produced at the final fracture. The analysis of kerf walls and floors allows essential information to be determined on the class of saw used in a dismemberment [3]. It is, however, more difficult to determine whether an individual saw has been used, and this relies on damage to the saw leaving a characteristic mark or, as we will demonstrate, examination of the bone using environmental scanning electron microscopy (ESEM).

This paper reports on the use of ESEM to characterize saw marks on bone with the aim of allowing forensic pathologists/scientists to match the witness marks on bone with saws used in dismemberment. It illustrates the two types of marks previously reported that can be imaged on bone and describes for the first time a previously unreported mark left on the bone that can be imaged by the ESEM and which may be used to identify a specific saw that has been used in the act of dismemberment.

## Classification and description of saws

A saw is essentially a piece of metal with teeth cut into it. The most basic discrimination between saws is the number of the teeth, which is measured in points per inch or teeth per inch. Most saws are set, which means that the teeth bend to alternate sides. The set widens the kerf width and helps prevent the blade from binding or bending. The set patterns can be any of the following:

– Alternate (most common), where the teeth are alternately bent in opposite lateral directions.
– Raker, where the raker is a specialized tooth that occurs every fifth to seventh tooth to rake materials or imperfections from the kerf floor. The rakers themselves are not set but the teeth between them are.
– Wavy set, where groups of teeth are alternately bent to the sides. Wavy-set saws have small teeth, which makes bending individual teeth difficult [3].

The shape of the saw tooth is also important, and this is generally classified as either rip or crosscut. Rip-cut teeth are flat chiselling teeth usually found on wood saws and designed to cut along the grain of the wood. Crosscut teeth are filed at opposing angles, typically 70°. The tooth terminates in a point and the teeth cut material rather than chisel it.

## Experimental method

To investigate whether saw marks on bone can be related to the instrument that made them, we have investigated saw marks from both a number of different saws and on different types of bone and synthetic analogs. Owing to the difficulties of using human bone for experiments, it was important to identify a suitable bone analog. A suitable analog should retain impressions in a similar way to human bone, should be of similar cross-sectional area, should be easy to obtain, and should be nondecaying.

Because there are significant difficulties associated with obtaining suitable tensile specimens from bone, a series of hardness tests were performed to identify the typical mechanical properties. Vickers hardness testing has previously been used to study the properties of bone by Weaver [5] and Zysset et al. [6] and has the advantage that the values obtained can be related to the yield stress of the material. A number of animal bones, pig femur and tibia, beef femur, venison, and lamb femur and tibia, were tested. The hardness test results were compared to the properties of a right femur from a deceased 74-year-old man whose bone was legally donated for research under the Human Tissue Act 1961 (Statutes in Force). Bone samples were prepared by extracting cubes of ~15 $mm^3$ using a deSouttre postmortem saw (deSoutter Medical, Hertfordshire, UK) and a pair of bone clippers. The samples were mounted in Struers Specifix-20, a room temperature setting resin, and then polished using standard metallographic preparation techniques to produce a flat, scratch-free surface.

The bone samples were oriented to allow testing either on the external surface of the cortex or at a number of points across the cortex. Hardness testing was then conducted using a Mitutoyo MVK-G1 Vickers hardness tester (Mitutoyo, Andover, UK) with a load of 1 kgf, a loading speed of 70 $\mu m\ s^{-1}$, and an indenter dwell time of

10 s. Indentations were made at three points across the cortex and the external surface, and six indentations were made to allow an average to be obtained.

Environmental scanning electron microscopy

ESEM was performed using a FEI Philips XL30 ESEM (FEI, Eindhoven, Netherlands). Typically secondary electron images, which carry topographic information, were obtained using the proprietary large field detector and imaging conditions of 15 kV and a spot size 5. The chamber pressure was 1 Torr, using water for the imaging gas.

Saw tests

A series of tests were made on pig femurs to investigate the different types of mark that could be seen on the kerf floor and the kerf wall. Additionally, a series of false-start kerfs were made to investigate whether or not saws could be identified from the measurements of kerf-floor width.

To investigate the effects of pressure, velocity (speed of cut), cutting angle, and number of teeth used on the witness marks, a series of tests were conducted on pig bone. In these tests, a saw was mounted in a Wickes professional miter saw (Wickes, Northampton, UK), as this allowed some variables to be controlled.

For the investigation of pressure, experiments were made to try attaching weights to the saw, but these often gave a skewing action on cutting. Therefore, a relatively subjective assessment of pressure was made with three distinctions: pressing hard, pressing soft, and using an intermediate pressure. To investigate the effects of speed, a Seiko DM-20 digital metronome (Seiko, Berkshire, UK) was used to dictate the speed of the cuts; samples were produced for fast (100 strokes per minute), medium (60 strokes per minute), and slow speeds (40 strokes per minute). In a typical dismemberment, it might be expected that initially frantic efforts are used, and then, as the sawyer becomes tired, fewer strokes per minute are used. Therefore, it was important to see whether this affects the type of marks that are left. Also, dismemberments may involve several people, and therefore, it is important to see whether the person sawing influences the marks left, as well as the effects from the tool.

Samples were produced with varying numbers of teeth in the cut. Tests were made with 100, 60, and 40 teeth involved in each stroke. The horizontal angle of cut was also varied and samples were produced at 90, 60, and 45° to the horizontal plane. To examine whether or not it was possible to uniquely identify a particular saw used, a series of blind trials were conducted by sawing in nylon 6.6. This material was chosen as it was found to display type C striations well (described below). Although Katterwe has previously recommended Mikrosil as a substitute material for the investigation of tool marks, this material contains residual plasticizer, which cannot be placed into the vacuum of the ESEM [7].

A crosscut saw was used, as rip-cut saws were found to fold the polymer and hinder identification. Chains of images were taken at a magnification of 100× using the ESEM. These images were taken and then stitched together in Adobe Photoshop Elements v2.0 (Adobe Systems, San Jose, CA, USA), and image matching was performed in ImagePro Plus v4.0 (Media Cybernetics, Berkshire, UK). A series of tests were performed. First, three sawyers were used to produce marks with four different saws: a Homebase Dynamic Teeth setting handsaw (Homebase, Stafford, UK), a Stanley jet cut saw with 7 teeth per inch (tpi) (Stanley, Sheffield, UK), a Stanley jet cut saw with 11 tpi (Stanley, Sheffield, UK), and a Jack hardpoint handsaw (Irwin Industrial Tools, Sheffield, UK). Subsequently, a test was made with four previously unused Jack Jackplus hardpoint handsaws (Irwin Industrial Tools, Sheffield, UK). This is commonly believed to be the most robust test of whether an identification is truly unique. Finally, an additional five previously unused Jack Jackplus hardpoint handsaws were tested to give additional confidence in the results.

## Results and discussion

Hardness testing

The results of the hardness testing are shown in Table 1. The average hardness of the surface of the human cortical bone was found to be 39.5 Vickers hardness number (VHN)

**Table 1** Average hardness values with standard deviation for a human cortical bone as compared to various animal bones

| | Hardness (kg mm$^{-2}$) surface hardness | Hardness (kg mm$^{-2}$) across cortex | Standard deviation surface cortex |
|---|---|---|---|
| Human cortical bone | 39.5 ($n$=8) | 39.4 ($n$=24) | 2.59<br>5.74 |
| Venison tibia | 54.8 ($n$=6) | 66.8 ($n$=18) | 4.76<br>3.78 |
| Pig femur | 26.0 ($n$=6) | 37.1 ($n$=19) | 1.00<br>4.42 |
| Lamb tibia | 32.6 ($n$=6) | 43.3 ($n$=18) | 1.37<br>4.03 |
| Lamb femur | 33.2 ($n$=6) | 44.1 ($n$=18) | 1.14<br>6.36 |
| Beef femur | 32.2 ($n$=6) | 46.5 ($n$=18) | 1.10<br>5.67 |

(or kg mm$^{-2}$). The average hardness across the cortex was found to be 39.4 VHN (or kg mm$^{-2}$). For the animal bones, it is noticeable that the surfaces hardness values are, on average, 24% less than across the cortex. The hardness of the surfaces were measured 1 day after the hardness measurements on the cortex, and the 24% difference may be explained by bacterial degradation leading to a softening of the bone [5]. The hardness results found here compare favorably with values from the literature [6, 8, 9]. It should be noted that variations in hardness values are found for different bones in the same individual and for people of different ages, and therefore, the data given here should be seen as an indication of the properties found rather than absolute values. The results for the hardness testing of the different animal bones showed that pig femur gave a reasonable match with the hardness of human bone. Additionally, it was found that pig femurs showed the same types of marks as human bones when cut; and therefore, because they were readily available for testing, these were used in subsequent experiments. The femurs were prepared by removing the proximal and distal ends of the bones and then removing the bone marrow from the shaft to provide tubes. All bones where then stored at −20°C until required. The bones were then thawed prior to testing.

## Kerf wall analysis

Previous analysis of saw marks on the kerf wall has largely been performed at low magnifications (typically 10–40×) using standard reflected light microscopy [2–4]. With ESEM, there are three types of striations that can be identified on the kerf wall, which are designated the alphabetical nomenclature within this paper as type A, B, and C striations. Figure 2 shows a diagrammatic representation of these striations, with Fig. 3 showing ESEM micrographs of the three types.

Type A striations are large bands that appear on the kerf wall bordered by deep furrows. These are clearly shown in Fig. 3a, the striations being typically 1–4 mm in size, representing the amount of material cut on each stroke. The deep furrows are produced as the saw is drawn backwards on the passive pull stroke when the teeth on the blade are all in alignment.

Type B and C striations can be clearly identified in Fig. 3b. Type B striations are multiple small striations that appear within type A striations. These are smaller bands that are typically in the region of 30–400 μm in size and are related to the amount of material that is cut by each individual tooth. The spacing of type B striations can be identified by the generally brighter bands on the ESEM image. The bright contrast arises from the fact that the emission of secondary electrons is strongly influenced by topography. Deeper, broader striations allow additional secondary electrons to be emitted from these regions, which manifest as brighter contrast on the image. In some cases, type B striations are difficult to define.

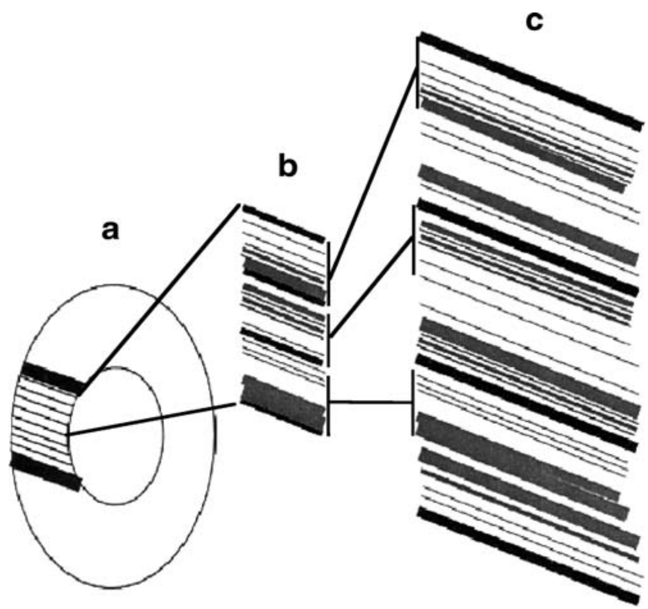


**Fig. 2** The different types of striations seen on the kerf wall under ESEM

Type C striations are seen within type B striations. Type C striations are highly irregular, with some bands smaller than 1 μm. These bands are created by imperfections along the leading edge of the saw teeth and are thought to be unique to each tooth (Fig. 4). Type C striations have not been previously reported in the literature and are only visible using the higher magnification available in the ESEM micrographs.

## Kerf floor analysis

Kerf floors are seen in three different types of cut. These can be classified as superficial false-start kerfs, breakaway spurs formed when the bone fractures, and deep false-start kerfs.

A range of kerf floors on breakaway spurs for nine different saws were examined using a stereo microscope (Olympus SZ-X12, Olympus, Tokyo, Japan). It was possible to clearly identify the kerf width from stereomicroscope images. Additionally, internal marks could sometimes be seen on the kerf floor. Previous investigators have noted that the kerf width correlates with the saw set [2, 3]. Different classes of saw have different teeth sets, as they are designed for differing applications; therefore, the kerf width should give a good indication of the saw class. Samples with breakaway spurs were prepared by clamping pig femurs in the vice and then cutting a 7–10-mm-thick section from the bone. A total of 90 samples were produced, of which 77 gave good-quality breakaway spurs.

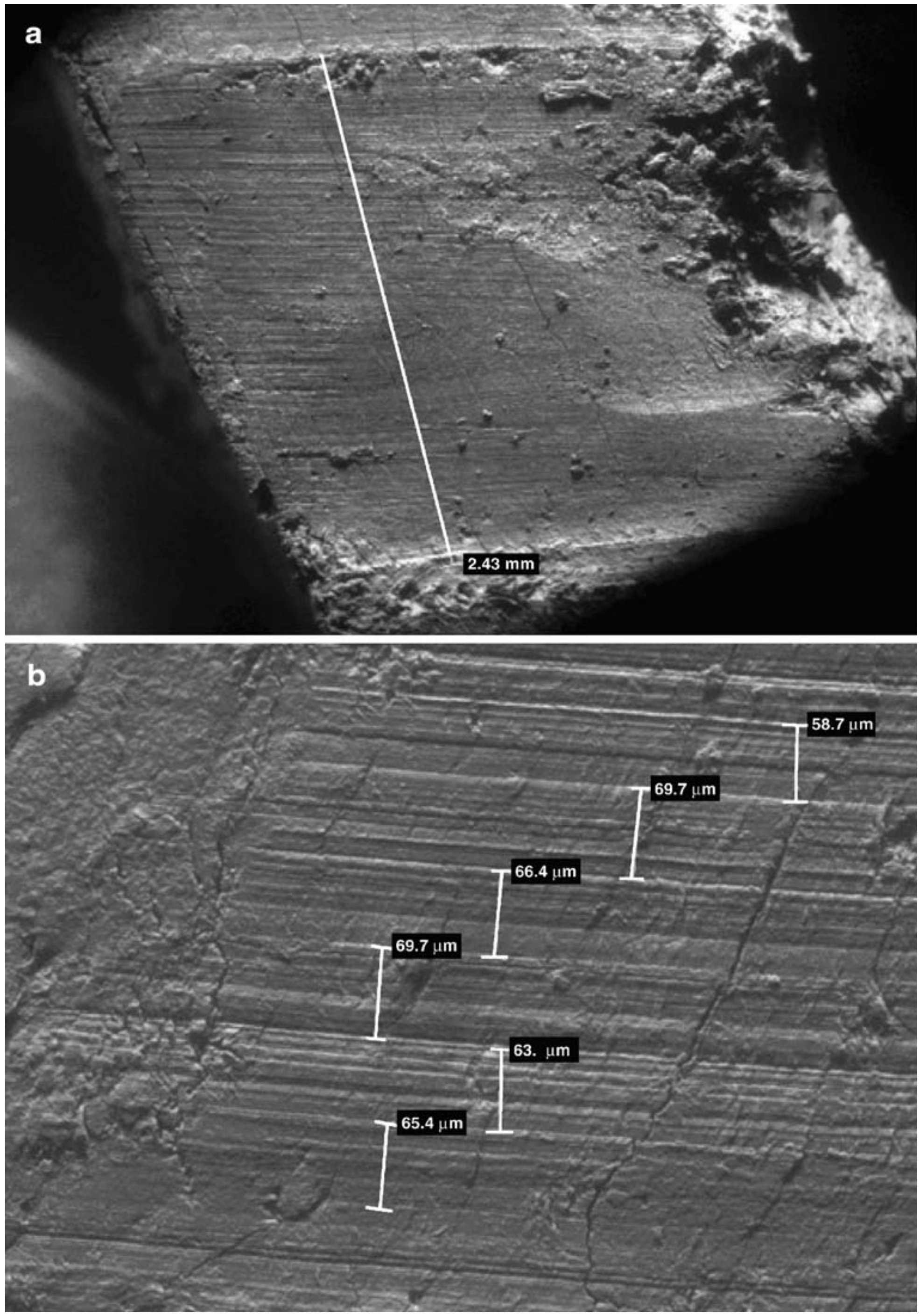


**Fig. 3** **a** Type A striation. **b** Type B (marked by the *white lines*) and C striations (*horizontal marks* within each type B striation). The spacings between type B striations are shown in the figure

The remaining 13 gave partial breakaway spurs, and these were discarded. After cutting, the samples were immersed in 10% formalin for 24 h, then removed and left to dry for at least 48 h for any shrinkage to stabilize. The degree of shrinkage was not quantified. The results for the different saws can be seen in Fig. 5, which shows that the kerf floor widths created by the different saws are often distinct, but not uniquely so. It can be seen that, generally, the values of kerf width are distinct, but there are several bands marked on the figure which show overlap between two different saw types. This demonstrates that if several saws are used in a dismemberment, then the kerf floor width can sometimes be used to identify which saw left which mark, but not if two (or more) saws give similar kerf widths. Typical examples of superficial false-start kerfs and deep false-starts in pig femur are shown in Fig. 6.

Superficial false-start kerfs have a high quality of kerf floor, which gives the best quality of information. Break-

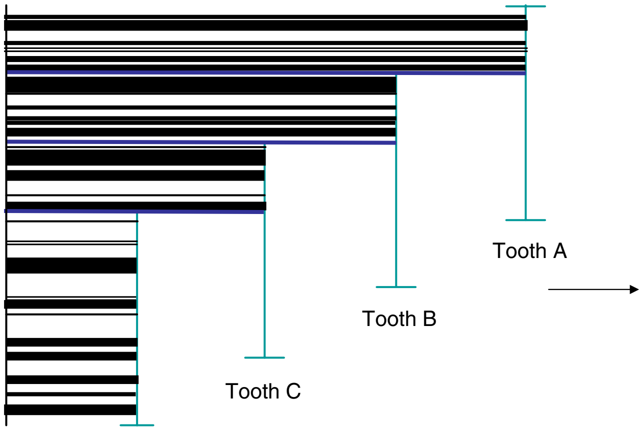


**Fig. 4** The theorized formation of type C striations caused by each tooth (for example, *teeth A–D*, etc.) in the direction of passage of the saw (*arrow*)

away spurs are variable in quality; sometimes the kerf floor is amenable to analysis, but often the kerf floor is incomplete. Deep false-start kerfs do not allow the kerf floor to be seen in any detail. It is possible to measure the width of the kerf, but the measurements show a large spread in the data, which makes interpretation difficult. Although it may be possible to see detail related to the set of the saw teeth, e.g., raker and nonraker, or even teeth detail, if other types of data are available, then these should be used for analysis (Fig. 7).

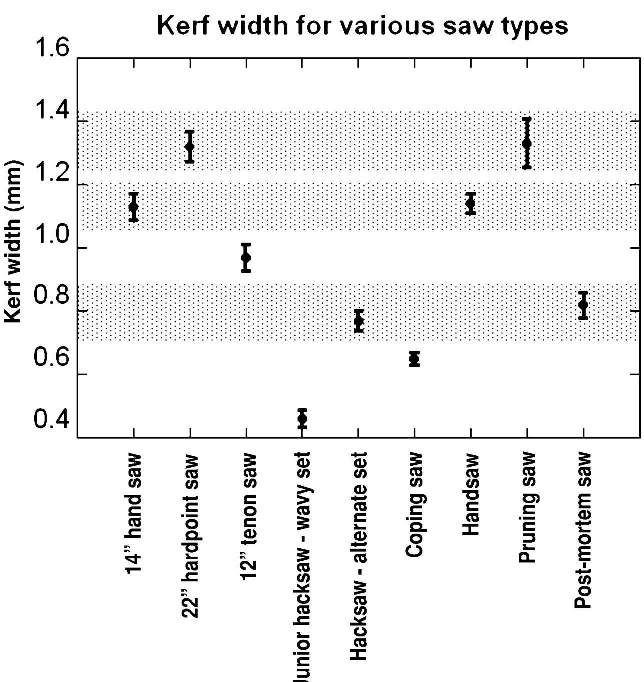


**Fig. 5** Kerf widths for different saw classes. The bands show overlapping kerf widths for different saw types, which indicate that these measurements can be used for identifying possibilities rather than unique implements

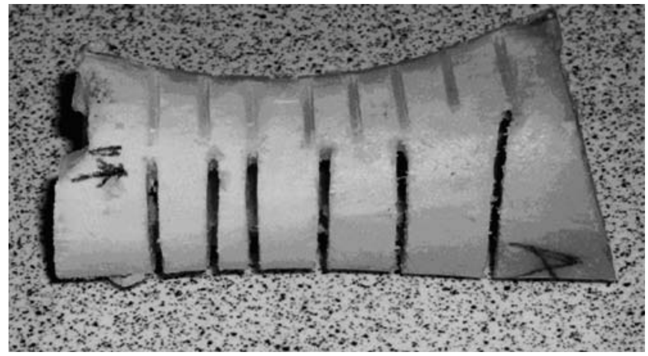

**Fig. 6** False-start kerfs (*top*) and kerf floors (*lower*) from trials in pig femur

## Effect of pressure, velocity, angle, and number of teeth

The experiments that investigated varying pressure used a relatively subjective approach of pressing hard, soft, and somewhere in-between, and the cutting speed was varied between 100, 60, and 40 strokes per minute. In practice, it was difficult to separate the effect of the two variables, as the harder the saw is pushed the faster the blade travels. As would be expected as pressure/velocity increased, fewer strokes were required to cut the bone. Detailed examination of type A and type B striations on kerf walls showed that, as the pressure/velocity increased, the spacing of the striations also increased. The number of type A striations seen correlated well with the number of strokes required to cut through the bone. However, the variation in spacing with pressure and velocity means that type A and type B striations do not offer a robust method for identifying a particular saw or class of saws.

The effect of varying cutting angle was found to vary the number of cuts to cleave the bone. The shallower the angle of attack, the greater the number of strokes required. The effect of varying the number of teeth in the cut also varied the number or strokes to cleave the bone. The more teeth in the cutting, the fewer the strokes required.

We postulate that type C striations are formed by the imperfections along the leading edge of a saw tooth, which means that they are related to the initial manufacture or the detailed way in which a saw has worn. The advantage of these (type C) striations is that as the user presses harder, more of a tooth is engaged in a cut; thus, the striation spacing remains constant but more type C striations are visible between the type B striations. This gives a unique way of identifying whether or not a particular saw has been used to form a cut.

## Blind trials

To investigate whether it is possible to uniquely identify a saw from the type C striations, four unidentified people were used to make saw cuts in nylon 6.6. Nylon 6.6 was

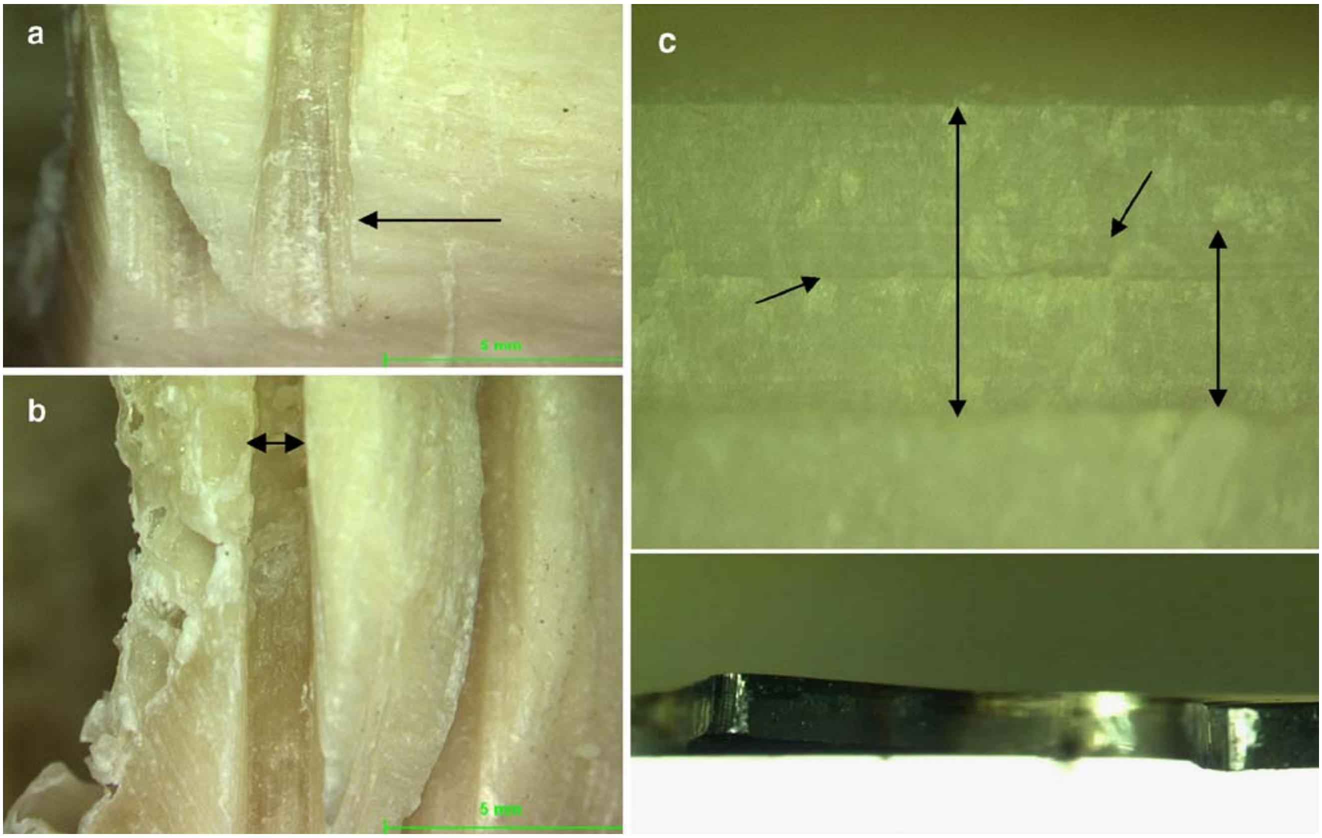


**Fig. 7** **a** A false kerf-start produced by a raker saw (*arrow*). **b** The width of the false-start kerf can be measured (*arrow*). **c** The marks in the base of the false-start kerf (*upper image*) caused by the teeth of the saw with the saw that caused the mark (*lower image*). Various measurements can be taken (*arrows*). Images taken with a stereomicroscope

chosen for these tests as bone is subject to drying and dimensional changes when placed in the ESEM.

Three of the unknown sawyers were men; two were competent saw users and one had little previous experience of sawing and was left handed. Each person made marks with four different saws and the marks were compared to marks produced by the same saws by one of the authors. An example of the matching of marks is shown in Fig. 8, which shows striation matching between the reference sample and three insets from other cuts made with this saw. It can be seen that there is an excellent correlation of the saw marks with the type C striations. Figure 9 shows examples of matching of marks from different saws by different sawyers. Again, there is excellent correlation between the images. For each participant in these tests, all the marks were correctly matched to the saw that produced them. This indicates that the marks are independent of the person involved in making the marks and are representative of the blade that was used to make them.

For the blind trials with the same make of unused saw (the previously unused Jack Jackplus hardpoint handsaws) four different sawyers were used: a female novice sawyer and the same three sawyers from the previous trial. Again, all the saws were matched correctly for each participant.

For the extension of the test with the same saw, a single sawyer was used, but there were now nine saws of the same type to match. Again, suspect marks were created and matched using the format previously applied. All nine groups of samples were correctly matched.

The blind trials show that type C striations are an excellent way of uniquely identifying a particular saw used to leave witness marks on materials. Burd and Kirk [10] state that greater than 60% correlation between striations is proof of positive identity. The type C striations can be matched with better correlation than this, showing that this is a robust method of tool identification.

However, to extend this ability to matching tools used in dismemberment, a method has to be found for correctly preserving the marks left on bone without shrinkage to enable examination of the striation spacing in the ESEM. Having said that, if one has a dismembered length of bone on which there is a kerf wall and one has one or more suspect saws available, then kerf walls could be produced with the suspect saws on this bone, away from the original wall, and all can then be examined within the same ESEM. This way, any bone shrinkage should apply to all samples from the same bone and type C comparison may then be possible.

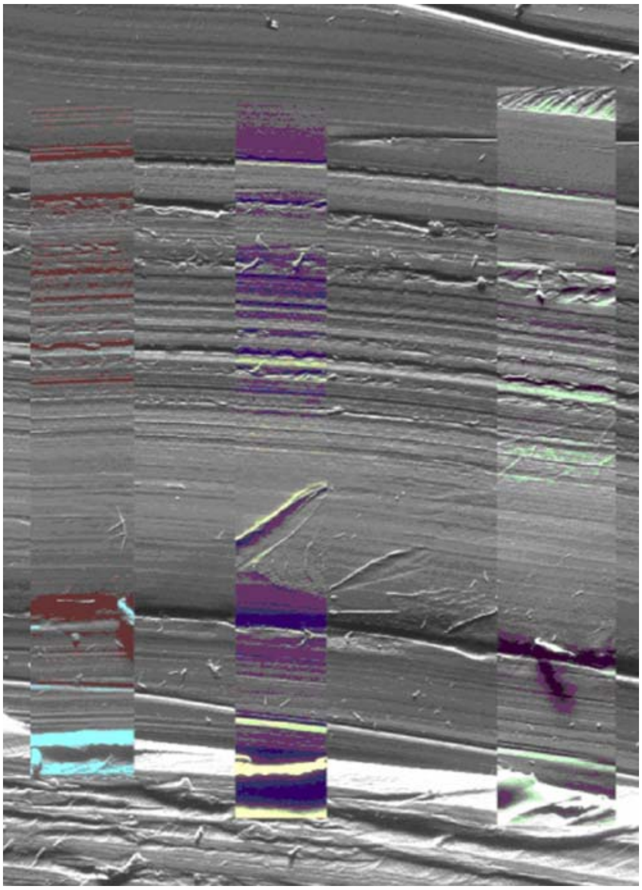

**Fig. 8** Matched type C striations. The three *insets* are marks made by the same tool that have been matched to the striation spacing as can be seen on close examination of the figure

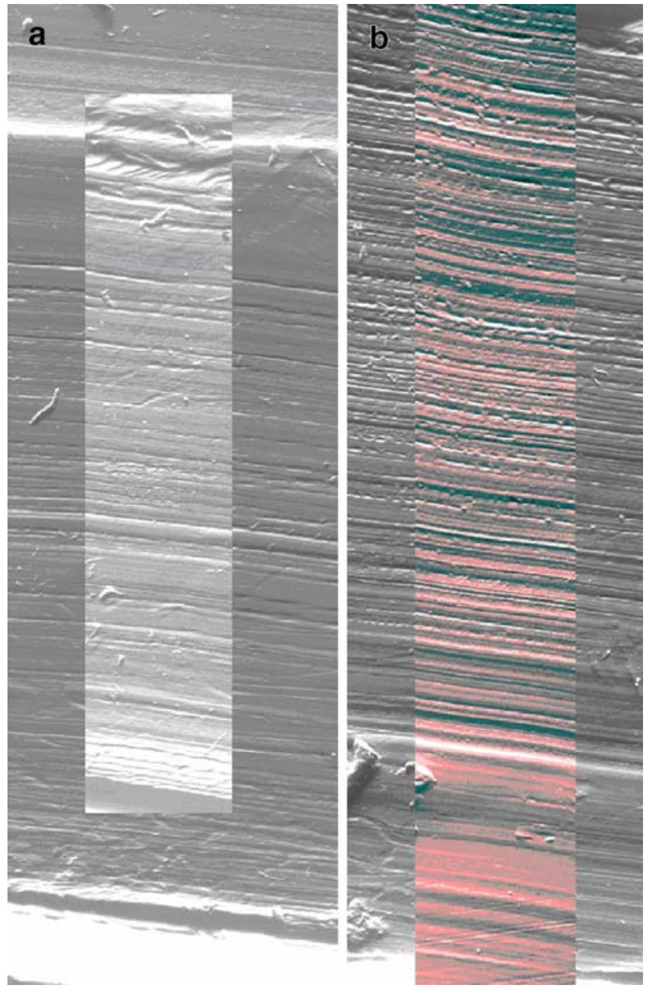


**Fig. 9** **a** Matching of type C striations for participant 1, saw 4, for the unused Jack JackPlus hardpoint handsaw trials. **b** Matching of type C striations for participant 4, saw 2, for the unused Jack JackPlus hardpoint handsaw trials

Finally, when multiple dismembered body parts are discovered, comparison of the kerf wall striations from different bones, for example, femur, humerus, and vertebrae, allows the investigator to consider whether one or more saws were used in the process of dismemberment of the body. Then again, if bones from several bodies are found, allowing for the effect of bone shrinkage, consideration can be made as to whether one saw was used on different bodies. Thus, in this scenario with the use of type C striations, it may be possible to link a series of dismemberments to one saw.

## Conclusions

The ESEM has allowed a comprehensive analysis of the striations and furrows left on bone by saws. The striations on the kerf wall can be classified into three types: type A, type B, and type C. This is the first report of type C striations, which have not been previously observed using standard reflected light microscopy techniques. Type C striations are unique to the tooth of the saw, and therefore offer the possibility of uniquely identifying whether or not a particular saw has been used in a case of dismemberment. In blind trials, nine identical saws could be correctly identified by matching type C striations in nylon 6.6.

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