The Identification and Classification of Sharp Force Trauma On Bone Using Low Power Microscopy

by

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A thesis submitted in partial fulfilment for the requirements of the degree of Doctor of Philosophy at the University of Central Lancashire

July 2012

Abstract

Cut mark analysis to date has been intermittently and superficially researched across a range of disciplines, despite its potential to significantly contribute to criminal investigation. The current study aims to elucidate cut mark analysis by proposing a novel classification system for the identification of knife cuts (kerfs) in bone. The system was devised, to record accurate and reliable information about cut marks and the criteria were tested for association with the knives that created them. Optical Microscopy was used to examine knife cuts on fleshed porcine bone. Incised cuts were made by a range of serrated, scalloped and fine-edged blades (n=9), by the author, and participants (n=23) were recruited to make marks on bone under the same force-measured conditions, using the Kistler force plate and a bespoke frame to control the level of height to which the knife can be raised above the bone prior to impact. Resultant kerfs were created by a single operator (n=86) and created by a range of individuals (n=186). The data suggests that consistent force was not achieved and the resultant marks on the bones made by the same knife had wide variation in their appearance and depth. The classification criteria tested did not provide discrete identification of knife blades from the assessment of kerf features; however, trends were identified from criteria including margin regularity, margin definition, floor width and wall gradient, which may form the basis for further investigation. Marks made by a single operator showed more significant associations ($p<0.05$) than group operators, and although kerfs from each share some trends, several significant relationships observed in marks made by a single operator are not shared by the participant group. Limitations of using optical microscopy included the inability to view all aspects of each mark, particularly when combined with variation in depth and angle produced by human operators. From the present results, it is suggested that the use of digital microscopy with a superior ability to build three dimensional images of indented marks would provide the necessary step forward to improve discrimination between knife classifications, based on the areas highlighted by the current research. This reinforces the need for further understanding of the mechanics of cut mark application in human individuals and their potential effects on kerf features.

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Acknowledgements

I would like to say a huge thank you to my supervisors, Jennie Robinson and Michael Wysocki, for their continued patience and support for the last 8 years. I would also like to express my gratitude to the School of Forensic and Investigative Sciences for funding this project, and giving me my initial role within the School; particularly Dr. Lee Chatfield, Dr. Allison Jones and Prof. Gary Bond, for their continued support. I would also like to thank Prof. Jaipaul Singh, for his continued guidance, advice and support, and Clare Altham and the rest of the staff in the Graduate Research School for their help throughout my studies.

This project has had valued input from many; I would particularly like to thank the technical support team; Sal Tracey, Clare Bedford, Jim Donnelly and Glen Crook. Sal, you are a legend, and there are scores of undergraduate and postgraduate students before me who will testify to that! Thanks for the help at all hours, and passing cuddles in the corridor, and patience with my project and my requests. Thanks to Clare for patiently sharing lab space with me and my project clutter, and help and guidance when exploring possibilities such as XRF. Thanks to Jim Donnelly for microscopy help. A big thanks also goes to Glen Crook for his patience in accommodating strange requests about stabbing things in his clean sports science laboratory, and help and support getting the force plate up and running. A final thanks to the rest of the technical support team who I may have pestered over the years!

I must thank Wisdom and Sons Butchers at Preston Market for kindly providing me with pig ribs and always responding to my many strange and specific requests with a smile and great service.

Running a project and studying has been challenging at times, and I would like to thank the FI team particularly for sharing the teaching burden approaching deadlines and when the worlds of research and teaching collided. Kev Pritchard - thanks for letting me say no sometimes, and your continued support throughout. Issy Colclough, Karen Lupton, Allan Scott, Nik Smith, and Adam

Wilcox; thanks for your offers of help, covering teaching, general support and just being great to work with.

I would also like to extend thanks to Dr. Colin Moffatt for his advice and suggestions on statistical analysis, and the patience to translate stats into a language I could make sense of.

I would also like to extend thanks to my examiners Dr. Jo Buckberry and Dr. Martin Smith, for reading my thesis and providing helpful and valuable thesis feedback and ideas for the future.

I would like to thank Dr. Tal Simmons as my transfer referee, and for her valued feedback.

There are many within the School and University who have also been there throughout the process; Dan Clark; thanks for being there to share the joys (!) and the less-than–joyous experiences of being a research student, and all the handbags, pasties and ex-parrots we managed to laugh about over the years. The fact we are still speaking after sharing a house, and office and a job for so many years is testament to your fabulousness. I have missed you!

Rach Cunliffe; thanks for help, feedback, getting me started and sharing your research experiences!

Jo Heaton; for your friendship and the time you have spent convincing me I can do this, and the teas, cake, biscuits and opportunities you have brought my way, thank you.

Catherine McQuade-Honnor – thanks for being a fabulous friend; swapping research student tales of woe and success over tea and sweet things, and always being there no matter what. I hope to repay the favour with babysitting duties now I have finished!

Eddie Prince; for sharing your unique wit, research experience, and encouragement throughout, thank you.

Claire Williamson; as my sole office buddy for the final stretch, thank you for everything; mopping up tears, sharing words of wisdom and advice, providing support and putting up with the chaos that is my (our!) workspace. Friends like you are essential survival tools for a thesis! That and the fact it never would have been handed in on time without you. You are amazing, and I hope to return the favour for you!

For my other friends, near and far; for the cards in the post, the emails, the late-night Facebook conversations, and words of encouragement; you are all stars, thank you.

To my family; thank you for believing in me and giving me all your love, support and encouragement to allow me to get this far. I am lucky to have you. I love you all dearly and look forward to spending much more time with you now the thesis is finally done!

Adam Wilcox; for picking me up, pushing me along, putting up with the long hours, tears, stress and everything else that came with part-time PhD study every day - I can never thank you enough. You helped me make sense of so much, and you always made me laugh when I needed it most. You are my rock - and I look forward to filling PhD-free hours having fun and catching up on all the time we've missed together – I love you.

There are many others who I many have not thanked by name, but your support and help over the years has been appreciated – please know that this final thank you is for you.

Chapter 1 Introduction

1.1 Research context

This study concerns the feasibility of identifying a particular weapon from the cut mark(s) it makes on the bone of a victim. An experiment was devised to produce, examine and document the individual marks of different knives, and from this, a method of establishing the identity of a weapon from the morphology of a single cut mark, or series of cut marks, is proposed. At the time of writing, no method of truly associating one knife with one mark on bone (known in forensic terms as individualisation) has been established; neither is there a dedicated method for establishing the type of knife from the examination of a mark on bone (known as classification), although many authors have mentioned the possibility and yet more have carried out research which is relevant to, and forms the basis of, the current study. These are detailed in the literature review chapter. However, a successful identification method to distinguish between metal knives has still not been established, a problem which this thesis seeks to redress.

Impetus for the current study came from the high proportion of knife crime in the UK, which has been a growing trend in recent years. Current data (Coleman *et al.* 2011) show that sharp instruments are the most frequent cause of homicidal deaths in the UK, and that this is an established trend over several decades (Figure 1.1). In 2010/11, the police recorded 32,714 offences using a knife or sharp instrument (Osbourne, 2011) including: homicide, attempted murder, threats to kill, Aggravated Bodily Harm (ABH), Grievous Bodily Harm (GBH), robbery, rape and sexual assault (*ibid*). The British Crime Survey (BCS) 2009/10 reports that homicides and attempted murders account for around 1% of all knife offences (Hall and Innes, 2010) and knives are the most common type of weapon used in violent incidents (*ibid.*). Provisional data show that there were 214 knife or sharp instrument homicides in 2010/2011, and 217 knife or sharp instrument attempted murders (Osbourne, 2011), Despite this, forensic knife wound analysis to date has been insufficient and as an area of research, inadequately addressed (Symes *et al*., 2002; Thompson and Inglis, 2009).

Specifically, there has been a dearth of studies using the ribs as the target bone, even though published data show that thoracic injuries are the most common in cases of criminal injury (Adelson, 1974; Hunt and Cowling, 1991; Rouse 1994; Rogde *et al.* 2000; Schmidt and Pollak, 2005). Banasr *et al.* (2003) report that thoracic injuries were the most common causes of death as a result of stab/incised wounds in their study (51.6%). The limited data on the frequency of bone injuries follow the same trend as the frequencies of soft-tissue injury; the thoracic area is the most common target, and Banasr *et al.* (2003) established that the highest proportion of bone and cartilage lesions in fatal cases are reported on the ribs and sternum. This thesis is novel in exclusively examining marks on ribs for forensic classification of knife cut marks; no other forensic publication examines ribs exclusively for this purpose.

Previous forensic studies involving knife trauma on bone tend to use methods to control the force and angle of the blow (Houck, 1998; Alunni-Perret *et al*., 2008). This thesis is novel in seeking to explore the possibility of mark identification from marks made by human subjects rather than mechanical means, and using knives as the sole weapon type.

If it became possible to identify beyond reasonable doubt that a particular knife made a cut mark then this would significantly improve the quality of police evidence and the security of convictions. Bringing the detection and certainty rate of knife identification up to a level equal to ballistic science would also enhance the deterrent already posed by strict sentencing and other crime prevention initiatives.

While the criminal application of knife mark analysis gives the present study its urgency, its application is by no means restricted to forensic science. Archaeology has formed the historical background to many modern studies, and in response, successful development of a technique to match individual implements with individual marks could have wide reaching implications for the reconstruction of human behaviour in archaeological contexts, including butchery sites, suspected cannibalism and others.

1.2 Aims of the thesis

Working hypothesis:

Knife blade characteristics create marks and features in bone related to their shape and form, and can be used to identify the type of blade that made the mark.

The aims of the project are to identify cut mark features that can be used to create a criteria-based assessment system in order to identify potential weapons from unknown marks. In order to achieve this aim, the following specific objectives are proposed:

- To categorise knives by identifying potential characteristics that may influence marks made in a surface medium.

- To identify features within a knife cut on bone that can be examined microscopically, and devise suitable classification criteria to be used for assessment.

- To use suitable statistical testing to confirm which, if any, kerf features can be associated with features of the knife blade.

- To test a range of individuals using knives to make marks on bone, to indicate the feasibility of wider application of criteria.

- To establish which knife cut features can be used to create a criteria-based assessment system to diagnose potential weapons from unknown marks.

This will be done first by reviewing the related literature, in order to utilise good practice and existing methods where appropriate and to develop the potential of existing methods, or flag up issues with other methodologies which can be resolved in the methodology to be developed. Secondly, a method of experimentation will be outlined based on the literature, but with original elements designed to address the specific issue of knife identification. The method will then be carried out as a series of experiments and the results detailed here, with the aim of making the technique reproducible by other practitioners for practical use. Finally, a discussion of the level of success, the likely application of the new method, and potential future developments will be given, the aim of which is to promote further testing, development and practical application of the research in the field.

1.3 Outline of chapters

After the introduction (chapter one), a comprehensive review of the literature pertaining to the current question is undertaken. This will involve a wide survey of several disparate academic fields and, as such, is split; chapter two focuses on archaeology, with a detailed background in mark analysis on bone. Chapter three discusses pertinent research in forensic science. Chapter four details considerations in experimental design and chapter five will propose and outline the new methodology to be implemented. Chapter six will describe the execution and results of the experiment, followed by chapter seven which will discuss the implications of the findings. Chapter eight will sum up the outcome of the thesis and note potential for future development.

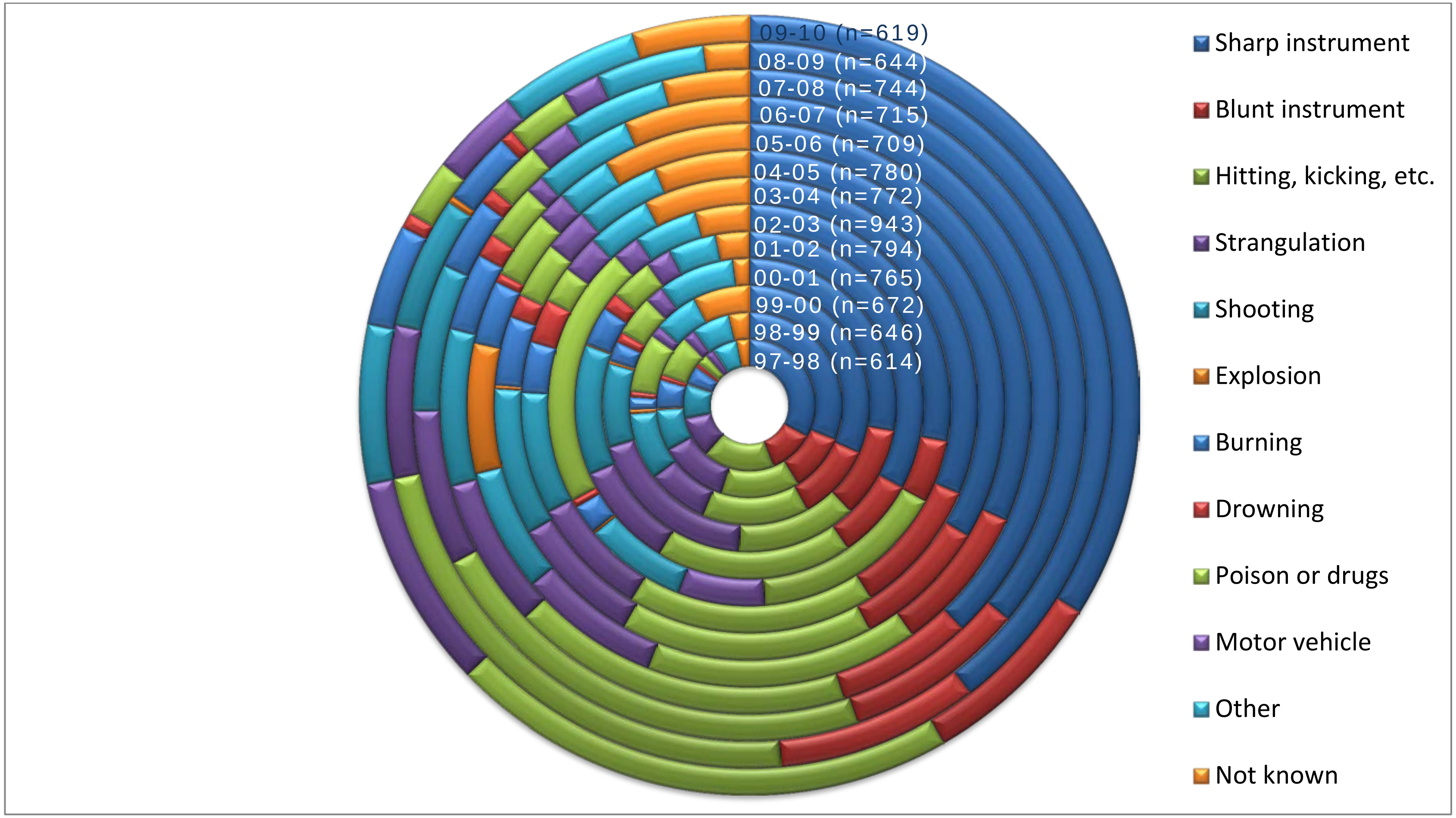

Figure 1.1: Cause of death (Homicide) in England and Wales (1997 to 2010). Data compiled from Coleman *et al.* (2011).

1.4 Abbreviations used

NID: National Injuries Database

SEM: Scanning Electron Microscopy

SFT: Sharp Force Trauma

F1-F3: Referring to fine knives used in the experiment

SC1-SC3: Referring to scalloped knives used in the experiment

SR1-SR3: Referring to serrated knives used in the experiment

MT: Medial tip of the kerf

LT: Lateral tip of the kef

MC: Main channel of the kerf

1.5 Definition of key terms

Class characteristics: Features that can be used to place subjects/objects into a particular group, but can never identify an individual subject.

Cut mark: the term cut mark is used to denote an incised mark created by tool such as a knife. The incision is made through a slicing motion, where the blade travels broadly parallel to the substrate being cut. This term encompasses stone, bone and metal tool marks.

Hacking trauma: Marks, often described as clefts or notches in bone, created by instruments used with chopping action, e.g. axes, cleavers, swords.

Individual characteristics: Features of a subject/object that can be used to distinguish a subject as an individual from other subjects of the same class.

Knife: A cutting instrument, consisting of a blade with a sharpened longitudinal edge fixed in a handle, either rigidly (such as a carving knife), or with a joint (pocket knife) (OED, 2012). *The Knives Act* 2007 defines a knife as "an instrument which has a blade or is sharply pointed". Knives can be distinguished from other weapons by their form and function. Knives as tools have a range of uses and can be used to stab, slice, cut, as well as chop. Swords are defined as "weapons, for cutting and thrusting, consisting of a handle or *hilt* with a cross-guard, and a straight or curved blade with both one or two sharp edges, and a sharp point (or sometimes with blunt edges, and used only for thrusting)" (OED, 2012).

Kerf: describes the channel formed by the progression of a knife through the bone (adapted from Symes, 1992). This is a specialised term to describe cut marks specifically made by knives or saws.

Patterned knives/blades: Used to describe knives or blades with teeth, e.g., steak knives and bread knives can have patterned blades.

Serrated edge: A saw-toothed edge (Wareing *et al.*, 2008). The teeth tend to be narrower than those found on a scalloped edge. Classification of serrated blades can be defined for the present study as blades with individual teeth measuring 1 mm or narrower.

Scalloped edge: A saw-toothed edge with wider teeth than a serrated blade. Classification of serrated blades can be defined for the present study as blades with individual teeth that are more than 1 mm wide.

Tapered ground edge or **fine edge**: A knife with a smooth unpatterned edge, the blade is ground to provide a fine cutting edge.

Chapter 2 Development of the discipline

2.1 Introduction

The history of the study of cut marks on bone has grown up largely in an archaeological tradition, rather than a forensic one. As such, studies have focussed on the reconstruction of butchery techniques, of distinguishing between marks made by natural taphonomic processes (such as tooth marks, weathering, etc.) and those made by human-made implements like stone, bone and metal tools. These studies have provided a strong groundwork for the current investigation and are detailed below; however, their archaeological nature has meant that key questions pertaining to the effect on ribs (the main area for criminal knife injury on bone, but poorly preserved in the archaeological record) and on fresh bone (with very different qualities to archaeological bone) have remained unanswered.

Forensic studies have long identified the potential to identify tools from marks made on a surface (Burd and Kirk, 1942), but in contrast to archaeological studies, examination of marks on bone is a much more recent introduction to research in this area. There are few studies that examine marks made by knives, with a much greater focus on hacking trauma. This literature is also detailed below. In each case there are elements of the methodology that later studies, including the present study, should seek to improve.

As with archaeology, the fact that forensic science has not focussed on the central issue of identifying damage on modern people means that there remain gaps in our knowledge that this thesis will seek to fill.

Paleoanthropologists and taphonomists also examine tool marks; however, rather than examining the range of surface types the forensic scientist might encounter, these specialists are concerned primarily in the investigation of surface damage on bone. There are numerous taphonomic processes that skeletal remains may undergo before discovery, and many papers document efforts at differentiating between deliberate or collateral modification made by sharp-edged implements, and other marks created by natural agents.

2.2 Archaeological studies

2.2.1 Introduction

In archaeological research, cut marks on bone are rarely examined exclusively. The retrospective nature of the discipline means that identifying a mark as a cut as opposed to anything else is a priority of many studies. Archaeologically speaking, this is of high importance as it defines deliberate, manufactured, human activity from natural agents that could be confused with human acts. Much of the earliest literature in this area is from Shipman and collaborators (Bunn, 1981; Potts and Shipman, 1981; Shipman, 1981, Shipman 1983; Olsen and Shipman, 1988) who sought to identify unknown marks that may mimic cut marks, including carnivore toothmarks, rodent gnawing marks, weathering, sedimentary abrasion, burning, root etching, and trampling. Cut marks on bone have also been examined in association with scavenger toothmarks, percussion marks, and modern excavation marks (Eickhoff and Herrman, 1985; Blumenshine *et al.*, 1996; Smith and Brickley, 2004; Loe and Cox, 2005; Bello and Soligo, 2008). There are also a number of papers that explore identification or classification of metal tools, usually in association with stone tools (Walker and Long, 1977; Olsen 1988; Greenfield, 1999; Bello and Soligo, 2008; Boschin and Crezzini, 2011) as well as a limited number of papers on metal edged weapons (Wenham, 1989 and Lewis, 2008). The aforementioned studies use a range of methods, and begin to explore classification criteria to distinguish between mark types, in order to interpret past events more accurately.

2.2.2 Seminal work

Walker and Long (1977) performed an early experimental study of tool marks, suggesting that the analysis of toolmarks on bones was useful to establish animal use in archaeological contexts. It combines the study of stone tools, with a metal blade and an axe, and discusses potential classification criteria for marks on bone. Experimental tool marks were made with two bifacially flaked obsidian flaked tools (coarse and fine flaked), a steel knife (it is assumed the blade has a fine or straight edge as it is not explicitly stated), and a small steel axe. The results later also refer to obsidian flakes with unmodified edges, but these are not mentioned in the original list in the materials and methods section. This study used fresh metapodials from cattle, which were dissected to remove adhering flesh down to the periosteum, and then mounted on platform scales to measure load during each cutting stroke. The remaining tissue was then removed by boiling and the marks were replicated using casting material. The casts were then replicated again to produce a negative impression. The cast replicate then had a central section removed and mounted onto a microscope slide with epoxy resin, and the surface was ground down to reveal a cross section of the mark. Examining a single portion of a whole mark for characteristic features does not necessarily ensure that it is representative of the rest of the mark. It would be valuable to establish how acknowledged variations in the cutting edge are reflected in the mark overall. The maximum width and depth was measured using a microscope fitted with a grid ocular. The results indicated that steel knives, steel axes and obsidian flakes with unmodified edges produce distinct V-shaped grooves that meet in a distinct apex; similar marks are produced by all three at the two lowest levels of load recorded (1 and 2 kg). The coarse and fine flaked stone tools showed a different cross-section shape without a single distinct apex and concave sides. Sawing motions with knives produced a series of parallel groves, and the flaked stone tools abraded the surface to produce shallow U-shaped groves that affect a large area of bone on either side of the cut. Depth of the marks was measured as a potential feature for classification, and only tools with very different morphologies could be differentiated by depth; Walker and Long (1977) do not offer further clarification on which of the experimental weapons this refers to. Mark width was also measured, and it was noted that at comparable pressures, the marks had very different widths. The authors also stated that obsidian and steel flakes produced similar groove markings (*ibid.*), which needs clarification as an earlier statement noting the variability of bifacially flaked stone tools would make this contradictory (*ibid.*). It may be assumed that the authors are referring to unretouched flakes, but clarification is needed, especially as unretouched obsidian flake tools are not mentioned prior to the results section. Axe marks were discernable from other tools by their depth to width ratio, suggested to be an artefact of the fact it is used with a chopping motion, rather than the slicing motion used with the other tools. Fine bifacially flaked stone tools produced narrower cuts than the coarsely flaked tools, and it is suggested that this could be a useful indicator of the degree of edge refinement for stone tools. Depth to width ratio of bifacially flaked blades does not show a significant correlation; however, steel knife and obsidian flakes did. The narrow regular surfaces of the cutting edges of these tools may have contributed to this; conversely, the irregular edges of the other tools are suggested as the reason for producing variable results with increasing load *(ibid.).* The authors then go on to mention that each tool could only be used effectively up to different loads; flake tools were difficult to use beyond 4 kg, whereas steel blades could be comfortably used up to 10-12 kg (*ibid.)*. The length of cutting edge allowed to contact the bone was also controlled at 35 mm. An additional experiment was conducted with the steel blade allowing 100 mm of the blade to contact the bone, and the marks produced higher means, indicating wider and deeper marks than the previous experiments (*ibid*.). This experiment was not carried out with any of the other tools; selecting a specific proportion of the blade rather than allowing a natural movement over the bone may result in marks with artificially high levels of similarity; and it should be considered whether previous experimental results with other weapons show the same degree of correlation if the length of the cutting edge was unrestricted in its movement over the bone.

Walker and Long (1977) conclude that their findings are useful to archaeologists for site interpretation, but also caution that pressure did make a difference to mark features and that there are a great deal of unknowns with weapon interaction and bone, therefore attribution of a particular tool with a tool mark is extremely difficult.

Although this early study looks to establish differences between stone and bone tools, there are a number of other studies concerned with the interpretation of cut marks with other taphonomic effects. Some of these studies use versions of classification criteria originally suggested by Walker and Long (1977), and other criteria are also observed and developed. The following literature examines the development and application of classification criteria for cut marks (also referred to as butchery marks) with the purpose of distinguishing them from other bone surface modifications.

2.2.3 Cut (butchery) marks and other bone modifications

Bunn (1981) discussed classification criteria in a different context; rather than distinguishing between weapons, it was suggested the width of a mark on bone could be used as a distinguishing feature between tooth and cut marks. Surfaces and broken edges of bones from Olduvai (Tanzania) and Koobi Fora (Kenya) were examined macroscopically with a strong light and observation of cut marks and hammer-related fracture patterns, carnivore and rodent-induced damage features, and weathering and post-depositional alterations were reported. Bunn stated that toothmarks can be distinguished macroscopically from cut marks by cross-sectional shape, and that cut marks are fine, in contrast to toothmarks which are broader (*ibid*.). The criterion is applied in an archaeological context and used for interpretation, without any known marks for comparison, relying on butchery interpretations from other archaeological sites This study improves on Walker and Long’s (1977) study by examining the mark as a whole, rather than looking at a single cross-section of the middle section, although it still involves the use of replicates rather than looking at the original mark.

Potts and Shipman (1981) suggested cross-sectional shape of the mark was a potential characteristic to differentiate between tooth marks and cut marks; Cut marks were suggested to leave V-shaped profiles, while tooth mark cross-sections were U-shaped. The cut mark findings are consistent with experimental work carried out by Walker and Long (1977); however, this study is not cited in the work by Potts and Shipman (1981). Like Bunn (1981), fossils from Olduvai Gorge were used to establish the mechanisms that may have caused the marks. A broad range of skeletal parts, taxa, and surface damage were included for a representative sample; 75 different surfaces were selected, some of which contained multiple marks (n=85). Bones were categorised into meat-bearing, (e.g., major limb bones and axial elements), and non-meat bearing, which include metapodials, podials and phalanges for the purposes of interpreting butchery practices. The fossils were brushed with solvent before casting to remove any preservatives, and then examined using a Scanning Electron Microscope (SEM). In order to identify the marks, several hundred control marks were made on modern bones for comparison; however no details of the methodology used to make the controls is included (e.g., animal species used for tooth mark production, type of tools used, and how many control marks were created and examined). A range of stone tool interactions with bone was defined, including chopping, scraping and slicing; definitions and morphology descriptions can be seen in Table 2.1. This study also replicated the marks by casting; the marks were examined using SEM rather than macroscopic examination like Bunn (1981) or microscopic examination as in Walker and Long (1977). Unlike Bunn (1981), Potts and Shipman (1981) made comparisons between known controls and Olduvai material, rather than comparing Olduvai material with other archaeological contexts. Potts and Shipman (1981) examined a range of marks on a wider anatomical/species range of bones than the Walker and Long (1977) study, with the same result. This study successfully applied a classification criterion of cross-section shape across a range of skeletal elements, and the mark casts were examined holistically, rather than in single sections. Shipman (1981) suggested the application of the SEM to examine various taphonomic processes because it offers superior resolution, greater depth of field, and higher magnification of specimens. Several hundred specimens of bone, including both fossil and modern examples were inspected under the SEM.

Mark Type	Cause	Morphology of Mark
Slicing	Edge of stone artefact drawn across bone surface in a direction continuous with long axis of the edge.	Cross section – may be V-shaped, can be variable. Always multiple fine striations within the main groove, oriented longitudinally Presence of "shoulder marks" Presence of "barbs"
Excavator (metal marks)	Metal tools slip and scratch the bone/fossil surface during excavation	May be fine, barely visible marks. V-U shaped in cross-section. Irregular, scalloped edges. Lighter in colour than surrounding bone.
Chopping	Stone artefact strikes a bone surface with a blow roughly perpendicular to the bone surface	Broad and V-shaped No striations Fragments of bone crushed inwards at the kerf floor.
Scraping	Artefact drawn across bone surface roughly perpendicular to the long axis of the edge.	Series of fine parallel striations across a broad area May lie below bone surface, but no readily identifiable lowest point

Table 2.1: Type and morphology of cut marks made by stone tools (data from Potts and Shipman (1981), Shipman, (1981) and Shipman and Rose (1983)

The following effects were investigated:

- Tooth marks made by non-hominids (tooth scratches, gnawing marks and punctures)
- Cut marks made by hominids (slicing, scraping and chopping marks made with stone tools)
- Marks made on fossils with modern metal excavation tools
- Spiral fracturing by weathering and hominids
- Burned bone
- Weathering
- Root-etching by grass plants

- Abrasion by sedimentary particles
- Digestion by predatory mammals and birds

The SEM was used to analyse microscopic effects of a variety of known taphonomic events on modern bones and teeth, and discover the causal mechanisms that produced such effects. Replicas were made of fossil surfaces with unknown taphonomic history, and then analysed with the purpose of evaluating the evidence of past events preserved on such surfaces, and deducing the taphonomic history of each specimen. After examining several hundred specimens, Shipman (1981) acknowledged that the sample size for some of these effects is very small, although she did not specify to which groups this applies. Much of this paper content overlaps with results presented in Potts and Shipman (1981). Tooth marks, stone tool and metal tool excavation marks were examined together as they produce grossly similar marks, which can be difficult to distinguish. She concluded that more work is needed to quantify results, enlarge sample sizes, and explore possible variability in effects, and proper techniques and good control samples were needed in order to do this. The method is not without limitations; restrictions in the sample sizes that can be examined due to the SEM chamber size, and sputter-coating of samples with precious metals in order to prevent charging is not always desirable (*ibid.*) The more recent introduction of ESEM (Environmental Scanning Electron Microscopy) means non-conductive samples may be examined in their natural state without modification or preparation (Kimseng and Miessel, 2001). Both techniques require access to high-cost equipment and staff with appropriate training. Initial studies were carried out microscopically (Walker and Long, 1977) and macroscopically (Bunn, 1981), and some classification features such as cross-section shape have been consistently identified at each level of examination. Identification of mark features that could be reliably identified macroscopically, or via the use of optical microscopy, would be advantageous. SEM/ESEM is not always widely available, increases costs, and in the case of SEM potentially requires time for sample preparation.

The use of microscopic (SEM) criteria to identify unknown marks on fossils was explored further in work by Shipman and Rose (1983). The study was undertaken in order to determine hominid butchery patterns; in order to recognise such patterns, it was proposed that non-hominid mimics should also be examined in order to be accurately and reliably eliminated as cut marks. Microscopic criteria has been suggested as a means to identify various unknown marks that may mimic cut marks, including: carnivore toothmarks, rodent gnawing marks, weathering, sedimentary abrasion, burning, root etching and trampling (Potts and Shipman, 1981; Shipman 1981a: 1981b, Shipman and Rose 1983). The focus of this study, however, included features of slicing marks, carnivore tooth scratches and gnawing marks. Over 300 slicing marks, 100 known carnivore tooth marks, and 175 known rodent gnawing marks were used in the experiments. Six possible variables were considered:

- Raw material from which the tools are made
- Interposition of soft tissue between the tool and the bone surface
- The repeated use of a single, un-retouched edge
- Mark directionality
- Mark sequence
- Waterborne sedimentary particle abrasion of cut-marked bones

In a forensic context, all of these variables are still relevant to some degree. The repeated use of an edge affects the individual characteristics of a type of weapon. It may be possible to observe when or if the individual characteristics change, how quickly, and by what degree. The presence or absence of soft tissue will affect the mark made, and data about the degree of soft tissue present depending on particular areas of the body, may give an indication of whether marks were made post-, peri-, or ante-mortem; this could be significant in determining the manner of death. Directionality may aid in establishing handedness of the individual, and should a suspect tool be found, handedness could be considered when making test marks for comparison. Abrasion and weathering, particularly in remains that have been exposed for extended periods of time, may also have an effect on any cut marks present, according to the destructive nature of the agents themselves. This should also be taken into consideration when comparing a “fresh” test mark and a range of marks that have been exposed to the elements.

Experiments were carried out with newly manufactured stone and bone tools and fresh bones, although the bone species and bone types used were not clearly specified in this paper. The bone surfaces were cleaned, and then cast prior to cutting, after cutting, and after boiling; this removed the remaining soft tissue whilst leaving bone surface morphology unaffected. Taking casts at each stage ensured that any marks made as a result of the cleaning process could be accounted for; however, the bones were cleared of tissue down to the level of the periosteum first. The results showed that marks consistently became narrower when the periosteum was removed; despite the very thin (less than 1 mm) layer of soft tissue, it still allows some protection from external damaging agents. Shipman and Rose, (1983) concluded that the presence of additional soft tissue, will protect bone from marks to an even greater degree.

Specimens were viewed under the following (variable) conditions:

- Tilts ranging from 0 to 45^{o}
- Orientations (rotation) from 0 to 360^{o}
- Magnifications from 10x to 1000x

Shipman and Rose (1983) observed marks made with bone and various stone-type blades, and found no apparent distinctions, with the exception of bone tool marks being generally shallower and broader than stone tool marks, observations could not identify an individual, unknown mark. The only metal marks examined were made accidentally, and no specific observations were documented. The instrument that inflicts cut marks or incised wounds in forensic casework, is almost certainly going to be manufactured from metal. Manufacturers may well use a range of metal compositions/metal types to make their tools, and this could have an impact on the mark made. However, it is the class characteristics of the tool (the tool type) that are likely to have the most significant impact on the type of mark created. Shipman and Rose (1983) observed that “some marks revealed features directly related to the morphology of the tools that made them”. They also document a phenomenon known as the “shoulder effect”, and have linked it to edge morphology. Shoulder marks are short marks that may accompany slicing marks and are made in the same stroke; they may be parallel or diverge from the main groove for part of its length. Such marks are thought to be caused by contact between the “shoulder” of the tool and the bone during the cutting action; they can be found at both ends of slicing marks, and are therefore discounted as an indicator of directionality (Shipman and Rose, 1983). Another feature observed during the experiment was the presence of barbs occurring at the heads and tails of slicing marks; apparently caused by small, involuntary motions of the hand either in the initiation or termination of a stroke.

Three variables were considered during part of the study examining repeated use of a tool:

- Presence or absence of diagnostic microscopic features
- Minimum and maximum width of slicing marks
- Details of microscopic features

A flint tool was used to make ten marks on a bovid innominate, and 250 marks on cleaned bovid ribs; the edge of the tool was kept perpendicular to the bone surface at all times for this part of the study. The sequence and direction of each mark was noted for later use in other experiments. In addition to replicating resultant marks, the edge of the tool was replicated before and after use.

All of the slicing marks created in this study had observable diagnostic features as described in the work undertaken previously by (Shipman and Rose, 1983) and others (Potts and Shipman, 1981, Shipman 1981a:b, 1983). Observations were also made regarding the change in mark detail; only one specific example was given - this was a comparison of the first and the 250th mark on the series of ribs, with similarities in the frequency and spacing on fine striations within the main groove (Shipman and Rose, 1983). The conclusion is made that microscopic features of cutmarks might be used to identify the particular tool that made them, if the tool edge had not been retouched, and if the motion used were similar throughout. This supports earlier work by Walker and Long (1977) who concluded that unretouched stone tools produced marks with a consistent cross-sectional shape, and that changes in pressure affect the marks made on bone.

Other work by Shipman (1983) considers criteria for distinguishing between different types of marks (cutmarks and tooth marks) including mark width and cross-sectional shape. This paper gives more details about controls than earlier publications. For the width criteria, 166 cut marks were made with stone tools of varying types, and 103 toothmarks of known origin were compared. Maximum and minimum widths were recorded with an ocular micrometer. The results indicated that the mean maximum width is not significantly different between tooth scratches and cutmark widths; however, the minimum width is significantly narrower in cut marks. Shipman (1983) states that three factors cause variation in cut mark width in butchery experiments:

- The angle at which the tool is used
- The amount of soft tissue between the tool and the bone surface
- The load applied to the tool

No further explanation is given as to how these conclusions were reached, and whether angles, amounts of soft tissue, or load were measured at any stage. Mark width is dismissed as an inaccurate criterion for identification of unknown marks, although Walker and Long (1977) found it useful in experimental studies for distinguishing between weapon types. Cross-section shape, although initially suggested by Potts and Shipman (1981) as diagnostic, on further analysis is also discounted as a reliable criterion because of the high levels of variation found. High levels of variation in the experimental study by Walker and Long (1977) was a result of bifacially flaked stone tools; unretouched stone tools left V-shaped profiles. Other factors, such as the amount of pressure applied may have had an effect on the marks producing variation, as well as the amount of flesh on the bones originally. The replicated marks from Olduvai came from a range of skeletal elements that had varying levels of meat and sinew. None of the experimental studies to date have examined the level of flesh beyond the periosteum and the effect it has on any mark made. This could have implications for context interpretations.

Eickhoff and Herrmann (1985) made experimental tooth and cut marks on bone, in order to compare the marks with surface marks on bone from a Neolithic Collection Grave (Odagsen, Lower Saxony). Their modern marks used fresh long bones of young pigs. The bones were boiled to remove adhering soft tissue. They used freshly made flint knives of various shapes to make slicing marks on the bone, and used canids and zoo animals to produce experimental tooth marks on bone. In experimental cutmarks, they observed narrowing at the ends of the marks, as well as a common “splitting-effect” (*ibid*.), where one or more lines originated from the main mark and take a diverging course. This was more commonly found at one end of the mark rather than at both, giving a branched appearance (*ibid*.) Mark depth showed little variability, but variation is said to be shown in relation to the contours of the bone. Previous work by Walker and Long (1977) indicated that depth as a characteristic was only useful to distinguish between tools with markedly different morphologies; the similarity in depth between cut marks may indicate use of similar tool types; any depth similarities between slicing cut marks and toothmarks may be as a result of their functional equivalence as asserted by Shipman (1981). They conclude that cut marks maintain a rigid course; that undulating forms are possible, but atypical. Tooth cusps are conical and more likely to yield and change course according to variations in the bone surface. Striations were viewed in both tooth and cut marks. Shipman (1981) had previously proposed striations as a feature that could be used to distinguish between slicing marks and tooth marks, which Eickhoff and Herrmann (1985) dismissed as a result of their findings. Overlap between the two classes of cut and tooth mark is acknowledged, and the authors (*ibid*.) state that splitting is the only characteristic that definitively identifies a cut mark from a tooth mark. Eickhoff and Herrmann (1985) attributed variations in form features to weathering effects on the mark. Shipman and Rose (1983) also observed that slicing marks can appear flatter and wider after being abraded. Eickhoff and Herrmann (1985) noted that weathering effects seemed to affect only the external bone structure which is open to the elements. The internal structure of the marks seemed to be mostly unaffected by any weathering process. Although it is not expressed overtly in the methodology, it is assumed that both authors made marks on bone as it is stated that the course of each cutmark is influenced by the person who made the mark on the bone.

Other surface modifications examined in association with cut marks include trampling; experiments were carried out on a variety of ovine and bovine bones (Olsen and Shipman, 1988). Classification criteria were also explored to distinguish between the two events. Trays were filled with four different grades of sediments (potting soil, fine sand, coarse sand, pea gravel), and fresh bones were placed in the trays, with enough space around them to allow movement in all directions. Human participants walked barefoot over the trays for two hours, and then bones were removed, washed and dried. Experimental butchery marks were prepared on an ovine metacarpal which was subjected to the same preparation as the rest of the bones (boiled to remove soft tissue, then remaining cartilage and periosteum removed with fingernails or plastic spatulas). The bones were examined using microscopy to check for marks and surfaces were cast using epoxy resin before any trampling or butchery marks were made. Trampling on bones was found to create a polish on the surfaces of long bones, and fine shallow striations were found on all long bones with the exception of those in the finest grade of sediment (soil). Long bones placed in trays of flint flakes exhibited shallow nicks that contained features similar to earlier described characteristics of chop marks (Table 2.1) in studies by Shipman *et al. (ibid.)* It was concluded that none of the trampling experiments produce marks that emulate cut marks in every detail; however, Olsen and Shipman (1988) suggest that interpretation of features on archaeological bone should require examination of a range of features. In addition to taking note of the sedimentary context of the bone assemblage, the following should be noted: frequency of modified bone, number of marks per bone, mark locations on the bone, mark orientation, morphology and depth and any association with polish (*ibid.*). Details of each criterion can be seen in Table 2.2 below. Caution is advised in relying on any single characteristic for identification, and the most reliable assessments should be based on consideration of all data (Olsen and Shipman, 1988).

Previous studies discussed rely heavily on SEM imaging of marks for interpretation (with the exception of Walker and Long, 1977 and Bunn, 1981). Blumenschine *et al.* (1996) suggest there are a number of disadvantages to reliance on SEM analysis including prohibitive time and financial costs, financial restrictions imposed and their effect on examining full assemblages, and an over-reliance on micromorphology of the mark, without considering the overall mark context.

Characteristic	Trampling marks	Cut (butchery) marks
Frequency of marks	Indiscriminate and found throughout affected assemblage	Localised on particular anatomical elements and parts thereof.
Number per bone	Very high – often difficult to count individual marks	Few distinct striations which may be readily counted.
Location	Widespread occurrence over diaphysis of long bones, little relation to muscle origins, insertion or other soft tissue attachments to bone	Systemic pattern of marks to areas of bone indicative of activities, e.g. skinning, filleting, disarticulation.
Orientation	Considerable variation in directionality	Orientation of marks related to a specific task, e.g. around joints, or longitudinal scraping marks
Morphology and Depth	Fine and shallow (superficial) with smooth walls and no internal parallel lines.	Deeper, V-shaped, internal parallel lines. Presence of chattering.
Association with polish	Extensive trampling creates general polish on bone surface	Polishes can form from handling/bone tool manufacture. More localised.

Table 2.2: Identification criteria for trampling marks and cut (butchery) marks. Data from Olsen and Shipman (1988)

They proposed a low-cost, high volume technique that provides a reliable alternative to SEM. In order to reliably determine the source of marks, three conditions are suggested including: analyst experience examining control collections, consistent application of published criteria, and the search for marks should be conducted using a hand lens or light microscope under strong light, systematically examining all parts of the surface at different angles to the light.

Marks to be identified included percussion, cut, and carnivore tooth marks from experimental assemblages produced by the authors. Like Shipman (1981), Blumenschine *et al.* (1996) distinguished between different types of cut marks, although the classifications are less specific: marks inflicted with a metal knife during defleshing and dearticulation, and scrape marks parallel to the long axis of the bone for removing the periosteum, were classified separately. Stone hammer and anvils were used to create percussion pits, grooves and microstriations (collectively called percussion marks). Toothmarks were tested for pits and scores (according to Binford, 1981). A minimum of 20 specimens was included so that the level of error would be reduced to 5% or less. The criteria proposed are shown in Table 2.3.

The first test examined inter-analyst correspondence for observation of the presence/absence of marks. Each of the three authors selected ten long bone shafts from their collections. On each shaft, a short 1-3 cm length section was selected at random and identified by strapping a rubber band around the shaft. 30 specimens were analysed macroscopically using the naked eye (five minutes), with a hand lens, and with a stereomicroscope at 16x magnification (approximately ten minutes per technique). Unsurprisingly, the lowest scoring method was using the naked eye, which was as low as 73% agreement between three observers, and increased to 80% between two. Using hand lenses/microscopy ranged from 80% agreement for three-way observations, and 100% for two. The second test explored a number of variables including the effect of micromorphological versus contextual data, experience of the analyst, different instrumentation (naked eye/hand lens/steromicroscope), and the effect of the analyst's familiarity with the type of bone surface on which the marks occur (smooth adult or flaky juvenile bovid bone). 20 specimens were selected, and a single mark was highlighted on each. Cut marks, tooth marks and percussion pits were all represented, and marks were selected on a range of criteria; some were included that showed all published criteria, and others were chosen because they lacked some of the criteria in Table 2.3.

Effector	Marks Produced	Morphological Criteria	Contextual Criteria
Teeth	Pit, score	High breadth/depth ratio Shallow U-shaped cross-section. Internal surface shows crushing Microstriations rare, occurring in low-density patches	Often multiple On cortical and medullary surfaces
Metal knife	Cut/Scrape mark	Low breadth/depth ratio for individual striae Deep V-shaped cross-section. Internal surface lacks crushing Internal surface with longitudinal microstraitions;	Subparallel groups Scrape marks broad shallow fields oriented parallel to long axis of bone, often with dimpling.
Hammerstone and anvil	Percussion pit and groove, isolated percussion microstrations.	High breadth/depth ratio for pits/grooves Internal surface lacks crushing Shallow microstriations in/and/or emanating from pits/grooves. Occurring in dense superficial patches.	Usually within 5 mm of fracture edge and restricted to cortical surface. Commonly found at or on opposite point of percussion impact.

Table 2.3: Criteria used for the classification of marks using low power microscopy (Bumenschine *et al.* 1996).

The authors, experienced in the field, unsurprisingly achieved very high results for locating marks (96.7% three-way correspondence) and a 99% accuracy rate for establishing known marks. Students, with some training and examination of control specimens prior to the test, identified 86% of marks which had all morphometric criteria present; rising to 90% in a second student group with more experience (Blumenschine *et al.* 1996). The study indicates that the application of diagnostic criteria for mark identification could be successfully applied in practice, as all of the marks examined were produced by the researchers. As they each produced their own marks, the study does not address how different operators using tools might affect micromorphological or contextual features of the marks and whether this would have an effect on the results. Eickhoff and Herrmann (1985) suggested that cut mark course varied according to operator; other features of variation have not been identified or discussed in this regard. The study also highlights that low power optical microscopy can be reliably used for the identification and classification of different bone modifications, although its usefulness in classification of marks with very similar qualities (such as those made by knife blades) has yet to be determined. Analysis of marks was conducted in approximately ten minutes; SEM analysis requires more time and preparation, which is prohibitive if examining a very large volume of samples (Blumenschine *et al.* 1996).

2.2.4 Cut marks – metal and stone tool comparisons

After the initial Walker and Long (1977) study which exclusively examined stone and metal tool cut marks, many subsequent works (as previously discussed) used the criteria suggested for cut marks, but instead focussed on cut marks in association with other bone modifications. Although toothmarks and cut marks were said to be functional equivalents (Shipman, 1981) there are class differences, and the development of criteria discussed to this point has focussed on distinguishing between marks made by very different classes of effector (e.g., sedimentary abrasion through trampling, percussion pits). Stone and metal tools developed to cut or slice have more potential for shared class features; this was shown when comparing unretouched stone tools with metal tools (Walker and Long, 1977). Marks made by tools that share the same function may be more difficult to distinguish and the development of criteria in order to do this is discussed below (Walker and Long, 1977).

Olsen (1988) explores the identification of stone and metal cut marks by examining bone and antler artefacts from a Bronze Age site, West Row Fen (Mildenhall, Suffolk), a Late Bronze Age site in Egham Runnymede Bridge (Surrey), and an Iron Age site in Fiskerton (Lincolnshire) to establish whether marks on the artefacts were made with stone or metal tools. West Row Fen artefacts contained some marks possibly attributable to metal tools, with many stone tool marks; Egham Runnymede Bridge artefacts exhibited more metal cut marks than West Row Fen, and Fiskerton artefacts contained the greatest number of metal toolmarks. Marks were examined macroscopically initially to identify manufacturing marks, and then a hand lens (10x) and stereomicroscope (18x) were used for identification of mark features. Finally, marks were cast and sputter-coated for SEM examination. Olsen (1988) examined marks from archaeological sites but gives no details of creation of any control marks for comparison with the artefacts, unlike the work Potts and Shipman (1981) and Eickhoff and Herrman (1985). Like Bunn (1981), Olsen (1988) examines a range of sites to interpret marks on bone (and antler) made by stone and metal tools; however, unlike the work of Walker and Long (1977), she gave no data to support general identification criteria proposed. Metal tools are said to make more uniform patterns on bone, and striations (if present) have a greater uniformity (Olsen, 1988); however, Walker and Long (1977) in experimental studies suggested that unretouched stone tools can leave similarly-shaped marks to metal blades, and that it is flaked stone tools that produce more variable marks. Examples are given of the repeated use of metal tools allowing striae in different marks to be compared and matched (Olsen, 1988) indicating that the same tool was used to make a number of different marks. This is applied to metal tools as the irregularities in the metal edges of tools do not wear as readily as those in stone tools (*ibid.)*. These observations and principles are transferable to the forensic analysis of metal blade marks. Olsen (1988) noted that parallel striae from different marks made by the same tool could sometimes be matched. This observation builds on previous findings about stone and bone tools marks exhibiting features related to the morphology of the tools that made them (Shipman and Rose, 1983). This potential for identification is exactly what the forensic investigator is interested in when trying to establish whether a particular object made characteristic marks recovered from a crime scene.

Stone and metal toolmarks are explored in more depth by Greenfield (1999) using SEM analysis; however, all marks in the study were made on soft pine wood rather than bone. This study used a much larger sample of steel blades (n=12) than other studies comparing stone and bone tools; it is also the only archaeological study to classify metal knife blades into two groups; serrated and flat-edged. The serrated-edged blades are further split into two sub groups; those with high and wide serration (e.g., bread cutting knives) and those with a low and tightly spaced serration (more saw-like in function). Details of the knives can be seen in Table 2.4.

.Greenfield (1999) describes superficially cross-sectional profile shapes, slope of the sides of the cut, and the evenness of the cut surface, as well as striations.

In addition to the largest sample for steel-edged blades, Greenfield (1999) also used 12 stone tools, each with different blade lengths and varying blade descriptions; previous studies examined (with the exception of Walker and Long,1977) do not give specific details of stone blade types used. Greenfield (1999) does not distinguish differences between unretouched and retouched stone tools (unlike Walker and Long, 1977); however, only one retouched tool was used, compared to 11 unretouched tools. V-shaped profiles are exhibited by stone and bone tools as in previous studies (Walker and Long, 1977; Potts and Shipman, 1981; Shipman 1981; Eickhoff and Herrmann, 1985; Blumenschine, 1999); stone tool profiles are more irregular, which was documented by Walker and Long (1977) and Olsen (1988). Stone knives also have one or more parallel ancillary striations. Metal blade knives produce flat-bottomed (I_I-shaped) profiles without additional striations. The presence of striations in stone tools has been observed by others including Shipman (1981) and Blumenschine *et al.* (1996). The study by Greenfield (1999) is the only example of wood being used as a medium for making marks (which were subsequently cast for examination). It is questionable whether the surface medium is an appropriate experimental substitute for bone; however, many of Greenfield's (1999) findings do support earlier experimental results, all carried out on bone. Bonte (1975) stated that bone can show instrument traces better than wood, therefore it is possible that further characteristic features may have been identified with marks made on bone rather than wood. Although ultimately concerned with marks on bone, the study by Greenfield (1999) used soft pine wood as a cutting medium to examine the cut mark profiles. Comparisons of

Knife type	Edge Type	Angle of V
Scalpel/razor for paper cutting	Flat-sided	Even V-shape
Medical Scalpel (used)	Flat-sided	Even V-shape
Medical Scalpel (used, broken tip)	Flat-sided	Even V-shape
Eating (table knife)	Flat-sided	Uneven V-shape
Eating (table knife)	Shallow, tightly spaced serration	N/A
Serrated steak knife	Deep and widely spaced serration	N/A
Bread cutting knife	Deep and widely spaced serration	N/A
Bread cutting knife	Small tightly spaced serration	N/A
Kitchen knife (wooden handle)	Flat-sided	Uneven V-shape
Kitchen knife (plastic handle)	Flat-sided	Uneven V-shape
Large Pocket folding knife	Flat-sided	Even V-shape
Small Pocket folding knife	Flat-sided	Even V-shape

Table 2.4: Summary of experimental test results for steel tools Greenfield (1999).

wood and bone and their response to different forces, such as compression forces, have not been published so wood may not necessarily reproduce marks in the same manner as bone. Processed wood (i.e., sanded and shaped) may not accurately replicate the contours of the bone surface, which may also affect the marks made. It may also contain residual marks from the tools used to process the wood. Recent advances in microscopy mean that digital optical microscopy is now an available option for analysis of samples. There are some more contemporary papers that explore stone and bone tools using digital optical microscopy, and examining both quantitative and qualitative aspects of cut marks.

Bello and Soligo (2008) used a 3D imaging microscope to capture 3D images of cutmarks made by a metal knife and knives than other similar studies flint flake, and used statistical models (linear regression) coupled with the image data to quantitatively measure a series of parameters, which are usually described qualitatively. Marks were made at angles of approximately 25^{o}, 45^{o}, and 90^{o} to the surface of pig ribs. As the methodology contains no details of removal of soft tissue, it is assumed that the ribs contained no flesh when the marks were made.
Profile cross-sections were taken at seven regularly spaced points along the cut mark, starting and ending at 0.5 mm from either tip. This is the first study to consider profile data from a number of points on the same mark. For each cross section, the following parameters were recorded:

- The angle between the slope of the cut mark and the uncut bone surface
- Opening angle of the cut mark (the angle between the walls at the floor)
- Bisector angle
- Shoulder heights (heights of shoulders formed at either side of the cut)
- Floor radius
- Perpendicular depth of cut

The results showed that some quantitative measurements could be used to differentiate between metal and flint tools (*ibid.*), supporting earlier findings by previous studies (Walker and Long, 1977) which also looked at only a single cross-section of the mark. The results also suggested that the angle of profile slope and the heights of the profile shoulders are related to the angle at which the tool is held (Bello and Soligo, 2008). This also supports the earlier findings of Walker and Long (1977). Work in forensic mark analysis by Alunni-Perret *et al.* (2005) discussed a feature known as “unilateral raising”, (raised ridges along the edge of a mark), which was attributed to the weapon entering the bone at an angle other than 90^{o}. Bello and Soligo (2008) report that the ratio of cut mark shoulder heights can be used to distinguish between weapon marks made perpendicular to the bone and marks made at more acute angles. There appears to be an increased difference in shoulder heights for weapon marks made at acute angles. An increased shoulder height may have been observed and documented by Alunni-Perret *et al.* (2005) as unilateral raising; once again, the application of quantitative data to mark features supports earlier qualitative observations. Bello and Soligo (2008) also highlight the variable nature of the cut itself, as the authors had difficulty in reproducing measurements along the cut, because profile parameters varied considerably along the mark; it is suggested that more measurements are required along the length of the cut mark for increased reliability. This also highlights an issue with the original study by Walker and Long (1977), as only a single cross-section was examined for the cut; and Bello and Soligo (2008) are suggesting that more than seven points need to be measured.

Digital optical microscopy was used by Boschin and Crezzini (2011) to build on the work of Bello and Soligo (2008). Butchery experiments were carried out on five fresh cattle autopodia (metapodials and phalanges) using different tools: a flint flake, a retouched flint tool, a modern steel blade (fine-edged), a modern bronze blade and a modern copper blade (Boschin and Crezzini, 2011), The range of weapons is greater than the flint tool and the knife blade used by Bello and Soligo (2008). The anatomical parts were frozen immediately after death, and frozen until the parts were butchered by the authors (Boschin and Crezzini, 2011). This study documented freezing samples before analysis; and studies have shown that freezing does not affect the hardness properties of bone provided it is freshly prepared before freezing (Weaver, 1966), and freezing samples was also employed by Saville *et al.* (2007).The bones were then boiled in water to remove the soft tissue, and buried for one month in order to degrease them. This methodology would not be suitable for forensic samples as a result of contamination issues. There are also no published studies that specifically examine the effect of burial on the morphological appearance of sharp force trauma. The butchery was undertaken by the authors, and the same anatomical parts were targeted to limit the data set variables. No details are given about the bones that were used, and whether they were comparable in size and shape; this could potentially affect marks made. The marks were also positioned in different locations to simulate butchery, and this may also have had an effect on the overall appearance of the mark.

The experimental marks (n= 61) were then compared with marks from two archaeological sites. The first site (Grotta Paglicci) samples comprised of 14 marks on bones from medium or large ungulates. A total of 17 of the marks were on shaft fragments, one mark was on a rib fragment, and the other on a tarsal. Trebbio (the second site) contained 15 marks from domestic species such as pigs. The location of marks included an innominate (n=1), radii (n=6), ulnae (n=2), metacarpals (n=3), metatarsals (n=2) and a tarsal (n=1), The location of marks on the archaeological samples has a greater range than the experimental group. This may be significant as previous studies indicate that hardness of bone varies between species (Weaver, 1966; Saville *et al.* 2007) and also that hardness varies between skeletal elements (Weaver, 1966), which may have an effect on the appearance of the marks as there are a range of species and skeletal elements used from the archaeological site. A digital optical microscope was used to observe the marks. Digital optical microscopy allows images to be layered in order to produce 3D composite images. Measurements were taken including:

- Depth of the cut mark
- Breadth at the top of the cut
- Breadth at the floor of the cut
- Opening angle at the floor of the cut

The depth of the cut was not able to discriminate between stone and bone tools. The opening angle of the floor in influenced by the edge of the tool – the bronze blade can be differentiated from the other blades using a Mann-Whitney U-test. The breadth at the top of the marks is not useful in discriminating between tools. The breadth at the floor is linked to the shape of the tool. Metal blades produce V-shaped or U shaped profiles, depending on the sharpness of the tool used (supporting work by authors such as Greenfield (1999)). Boschin and Crezzini (2011) describe infrequent ancillary ridges on one side and attribute them (as well as internal microstriations) to anomalies of the cutting edge (e.g., damage). There are no images or further description of these ridges/striations, so it is difficult to establish whether there are comparable features in any other studies. Stone and flint tools produced distinguishably different patterns, though some degree of overlap is present in a few of the samples (*ibid*.).

This broadens the weapon range from the knife blade and stone tools used by Bello and Soligo (2008), by comparing knife blades made of different metals, and different stone tools. It indicates that the opening angle of the floor of the cut is able to distinguish between the bronze blade and the steel blade used as part of the study. The varying hardness of the metals may have had an impact on the shape of the blade over time and use - steel is harder than copper or bronze (Zahner, 1995) and therefore less likely to be blunted when used. This is the first archaeological paper to directly compare different types of knife blades and demonstrate that cuts can exhibit different marks on bone; however, it is not reliably discriminatory (Boschin and Crezzini, 2011). The authors also only examined one point on the cut, at the midpoint; this does not take into account the possible variation that may occur over the length of the mark.

Having explored archaeological research in terms of comparative studies of cut marks made with stone and metal tools, and also with other bone modifications, the final section examines two archaeological papers that explore metal edged weapons exclusively.

2.2.5 Cut marks – metal weapons

Wenham (1989) detailed criteria for the classification of metal edged-weapon injuries based on experimental marks made with a variety of bladed weapons and comparison with existing marks on six archaeological skeletons. Wenham (1989) does not detail his experimental methods, but he does make use of light microscopy and scanning electron microscopy in assessing the marks. The following criteria were proposed to classify a mark as produced by an edged-weapon (Wenham 1989):

1. Linearity, without large irregularities in the line of the injury
2. An edge to the injury which is well-defined and clean
3. A cut bone surface which is flat and smooth and in some cases, polished
4. The presence of parallel scratch marks on some cut bone surfaces

The generalised criteria combined with the lack of methodological details (such as sample numbers and weapon types) means that reproducing the work would be difficult. However, Wenham (1989) does recognise the potential for the use of light microscopy and SEM in the analysis of metal edged-weapon injuries.

A more recent study of metal edged-weapons is reported by Lewis (2008). Marks were created on fleshed bovine tibae with uncontrolled force and direction. Six different sword types (a total of 68 marks examined) were compared with one type of hunting knife (24 marks examined). Cut marks were examined macroscopically, and using low power microscopy when required; however, Lewis (2008) does not specify in which cases this was necessary. Eight traits (cut length, shape, feathering, flaking, cracking, breakage, shards, and the direction of impact) were assessed and assigned a score. Each weapon was said to be representative of its class; it was proposed that sword marks can be differentiated from knife marks, and additionally, some of the swords can be identified based on features observed in the marks they made on bone. There were degrees of overlap between different classes of sword, and it was acknowledged that some different sword classes can make similar types of mark (Lewis, 2008) which is consistent with findings by Wenham (1989) that different weapons could produce similar-looking marks. However, it was also acknowledged that the same blade can also exhibit variation in mark type (Lewis, 2008). This may be the result of differences in operator application (such as the angle and force used), and the interaction between bone and blade – the bones had freedom to move and therefore there may be variation in the location of the mark on the bone and positioning of the blade as it meets the surface. It is suggested that a sufficient number of marks (circa ten) are necessary to make a reliable assessment of sword class (Lewis, 2008). As the same weapon can produce a range of marks, examining a large number ensures that the investigator can establish the range of morphology for the weapon under experimental conditions. Needing ten marks to make an assessment could be prohibitive in practice, where the actual number of marks on bone may be fewer, especially in forensic cases where published data records few cases of bone and cartilage lesions (Banasr *et al.,* 2003). The weapons used were selected as typical examples of their class (Lewis, 2008). The single knife class representative was a hunting knife; but knives vary in their style, blade shape, size and pattern, and comparison with different types of knife blade should be carried out to ensure the differentiation between swords and knives applies to more than one specific type of knife. The number of marks examined for the knife (n=24) was greater than that for each sword type (an average of 11 marks per sword). It is concluded (*ibid.*) that the minimum number of marks required is ten, and yet the largest number of marks made by a sword type is 18, and the smallest ten; the minimum number of marks is the same as the smallest number of marks examined.

Lewis (2008) acknowledges the need to accurately and precisely quantify aspects of cut mark morphology in order to reliably identify blade type. The differences between knife cuts and sword cuts are proposed to be macroscopically visible (*ibid.*); cut marks produced by swords may lend themselves more to macroscopic evaluation and differentiation than knives as a result of their size. The fact that visible differences between sword cuts in bone are noted (*ibid.*) indicates that there could be potential for knife blades of different types to be distinguished, although the application of low power microscopy would be more appropriate because knife marks (and therefore distinguishing class characteristics) are likely to be smaller and difficult to reliably observe macroscopically. Using six different sword types is a wider range of weapons than other published studies; however, the number of replicate marks should be increased based on the recommendation that the minimum number to assess class features is the same as the smallest number of replicates used for one sword. The fact that the bones were allowed some mobility, and the swords were used by hand and not applied by machine may allow variation in the interaction between bone and blade. By having a high number of replicates, investigators can observe the full range of marks created by a given weapon, and check for overlapping class features with other weapons.

2.2.6 Summary

Some archaeological studies to date have tried to establish the type of tool that creates marks on bone. In comparison, forensic tool mark examination has established principles which form the basis of analysis, such as the identification and comparison of potential class and individual characteristics, with the aim of establishing the highest level of classification possible, and to identify the original tool that made the suspect marks. The level of classification required in archaeological studies is much more basic than this, and there is no advantage or need in publications to identify a specific weapon that made the mark; establishing the weapon type still largely rests on distinguishing between very different classes of weapons such as stone and metal tools. Some findings from these studies may be transferable to forensic analysis of metal weapons, but still no studies exist that seek to identify knife classification criteria for the same type and size of weapon, with different blade features (as addressed by this thesis).

Chapter 3 Studies in Forensic Science

3.1 Introduction

Tool mark identification from marks made on a variety of surfaces is a well-established practice in forensic investigation. Burd and Kirk (1942) suggested that a mark left by the end of a sharp instrument may be sufficiently characteristic for identification, referring to marks made on wooden, metal or other smooth surfaces. Bonte (1975) established that the effect of sharp force trauma (SFT) on human bone is consistent with SFT effects on inanimate materials (such as wood or metal), indicating that sharp instruments can leave recognisable traces in bone. The chief areas of analysis on bone in a forensic context include weapon identification from mark analysis in skin and cartilage (Sitiene *et al.* 2006), saw mark and dismemberment analysis (Symes, 1992; Symes, Berryman and Smith, 1996; Saville and Rutty, 2006), and weapon identification from mark analysis in in bone (Houck, 1998, Bartelink *et al.,* 2001, Humphrey and Hutchinson, 2001, Tucker *et al.*, 2001, Alunni-Perret *et al.*, 2005). In the context of this study, it is the latter category that is most relevant to the focus of this thesis on knife trauma. Other areas do still provide useful information with potential to develop the area of knife trauma analysis on bone. Before discussing each of these areas in turn, it is appropriate to define different types of sharp force trauma to be referred to throughout these sections.

3.2 Sharp force trauma identification in bone

Sharp trauma on bone is caused by narrowly focussed, dynamic compression forces, applied to a bone's surface (Byers, 2002) and can be created by a variety of weapons and tools (Symes *et al.* 2010). If enough force is applied, a wound will form at the point of impact, and may be classified as:

- **Punctures**: Marks caused by instruments placed at a vertical (or nearly vertical) direction to the bone surface, and can have a conical shape (Byers, 2002). Examples of punctures include stab wounds, if only the tip of the knife blade punctures the bone surface.

- **Clefts/Notches**: The result of a vertically applied, dynamic force with an instrument that has a long, sharp edge, typically a result of hacking trauma (Byers, 2002). Axes, cleavers, or machetes are typical examples of implements that may produce this kind of mark. These marks are also typical marks made on the superior and inferior margins of ribs if a knife is inserted between them (Maples, 1986).

- **Incisions**: These are so classified because the wounds are longer than they are wide. Incisions on bone occur when a force is applied across the surface of the bone with an instrument containing a long, sharp edge. Incisions on bone can also occur as a result of stab wounds through the layers of soft tissue covering the bone, creating a superficial incision whilst travelling over the bone surface (Symes *et al.* 2010). Mason and Purdue (2000) further define incised wounds as those delivered in the plane of a sharp edge, and which directly reflect the edge sharpness. Most incised wounds to bone are created by some sort of knife (Symes *et al.* 2010), although saw marks also come under this category.

This thesis focuses on forensic analysis of incision marks on bone made by knives. Knives are the chief focus of very few studies, but have been examined in conjunction with saws and hacking trauma. Forensic studies, like the archaeological studies discussed in Chapter 2, have examined a range of features that could be used to distinguish between different types of marks in bone. Unlike the archaeological studies, forensic analysis has the ultimate goal of establishing that a particular mark can be associated with a specific individual weapon and no other. This concept is explained further in Section 3.7.

3.3 Weapon identification from mark analysis in skin and cartilage

The pathological analysis of flesh wounds can establish weapon type by wound shape, edge characteristics and, rarely, by comparison of a blade with remaining fragments in soft tissue (Adelson, 1974; DiMaio and DiMaio, 1993). Homicidal stab wounds may result in trauma to both soft tissue and bone. When this is the case, it is important to understand how the injuries should be described in each circumstance.

A distinction should be made between terms used when describing trauma in the soft tissues of the skin, and effects observed on bone. Soft tissue injuries as a result of SFT are known as incised wounds (Rutty, 2000). Cut wounds of the skin are as a result of a knife being drawn across the surface of the skin, with enough pressure to produce a wound longer than it is deep. Stab wounds result from the penetration of a pointed instrument into the depth of the body, causing a wound deeper than its surface length (Spitz, 1993; Rutty, 2000). In soft tissue stab injuries, the dimensions should be recorded to estimate possible blade width; however, the skin stretches upon impact of the blade, and therefore the width can be underestimated (Rutty, 2000). The width recorded may also depend on how far the blade passes into the body. Depth of penetration should also be recorded as this can give an estimate of the length of the blade, but it should be remembered than in areas of the body where the surface can be compressed (such as the chest cavity), the length may be overstated (*ibid*.)

Sitiene *et al.* (2007) attempted to identify tool characteristics from soft tissue in 489 autopsy cases from 1995-2004. Around 85% of cases had knives (n=835) submitted as potential causes for the injuries. Another 42% had injured rib cartilage in addition to skin wounds. Similarly, 5.5% of cases allowed knife identification based on skin wound and cartilage features, and 2.6% of cases were identified based on skin wounds alone. A polythene membrane was used to record features for comparison with skin wounds; there is no justification for the use of polyethene for the comparative analysis of marks in skin. Little detail is given of features used for the comparison of marks with cartilage, unlike the study by Bonte (1975). Although the study examines a large number of cases, little experimental detail is given. The accuracy of stab comparisons made in a polythene sheet for matching with those made in skin is also uncorroborated.

Although analysis of soft tissue can be used for the examination of knife wounds, the rigidity of bone means that the dimensions and shapes of wounds are better maintained than in skin and other soft tissues (Spitz, 1993). The following sections explore this assertion, examining a range of sharp weapons making marks in bone, and making an attempt to identify the type of weapon, and sometimes the specific individual weapon from macroscopic, and microscopic (optical and SEM) analysis of bone.

3.4 Saw mark and dismemberment analysis

Select studies have examined saw mark analysis in increasing detail as the potential for identification of knife and saw marks has been recognised for some time; Bonte (1975) briefly discussed stab injuries in cartilage, and described the observation of parallel "rills" (striations or grooves) that correspond to serrations on the knife blade. Bonte (1975) also explained that light microscopy is a useful technique for examining the knife cuts, before moving on to discuss the absence of information about saw marks and their potential to provide useful investigative information. This includes rills observed at the bottom of a partially sawed portion of bone, giving information about the set of the saw and the gauge of the saw blade. Very little specific information is given about classification, but it is stated that many saw features can be compared between a mark and the tool. Andahl (1978) conducted a more expansive discussion of the topic of saws and mark analysis, suggesting characteristics of crime scene marks to be examined. These include:

1. **Striation patterns**: Saw striations are complicated patterns and cannot be explained in the same way as single-action toolmarks (Andahl, 1978). The striation patterns described appear to be the equivalent of those mentioned by Bonte (1975), but described instead as "rills".
2. **Wave formations**: The result of saw actions stopping/jamming, and then released and sawing begins again. Distance between the crests of the waves gives distance between individual teeth and therefore teeth per unit length.
3. **Swarf lips**: These can be used to ascertain direction of the cut but are not defined in this paper, and no explanation is given as to how they are formed (Andahl, 1978).

The paper suggests that from the cuts made by saws, information can be obtained including the number of teeth per unit length of the saw, degree of wear, direction of cut and condition of the blade (Andahl 1978). Cuts were examined using a low power microscope up to 40x magnification, and made of materials including metal rods, bone and wood. Wood grain was said to obscure some cut features when viewed microscopically, and it was also stated that lighting can be a problem with bone (Andahl, 1978).

Andahl (1978) gave more detailed descriptions of characteristics than Bonte (1975), and examined saw marks on a range of surfaces (including bone); however, Symes (1992) used these studies as the basis for a much more detailed examination of a range of saws and the types of features they leave in bone. Both commercially available and specialist saw examples were used to make marks on human long bone shaft with the purpose of diagnosing features within the cut as a product of specific blade actions. These features (class characteristics) could then be used to narrow the range of saws used to make a particular cut (Symes, 1992). Each saw made ten consecutive cuts on the shaft - the bones were supported at one end by a vice, and cuts made by the same individual. The shafts are received in a procured, fresh state; each bone was then immersed in diluted bleach (sodium hyperchlorite) solution (3%) for 25 minutes then simmered over low heat in a solution of water and degreaser for one to two hours; Symes (1992) states that it is assumed this does not compromise the visible evidence or elastic properties of the bone. The bones were examined using light microscopy up to 40x magnification.

Symes (1992) defined the word “kerf” to describe the channel formed by the progression of the saw through the bone (Figure 3.1). This term was initially used in reference to saw marks, but is also later applied to knife marks (Symes *et al*., 1998; Symes, 2002). Symes (1992) also defined the kerf “walls” and “floor”, and, for saw mark analysis, suggests that the walls and the floor must both be examined, because the kerf floors, when present, offer the most information about the points of each tooth and the points of the blade of the saw (Symes, 1992; Symes *et al.* 2010).

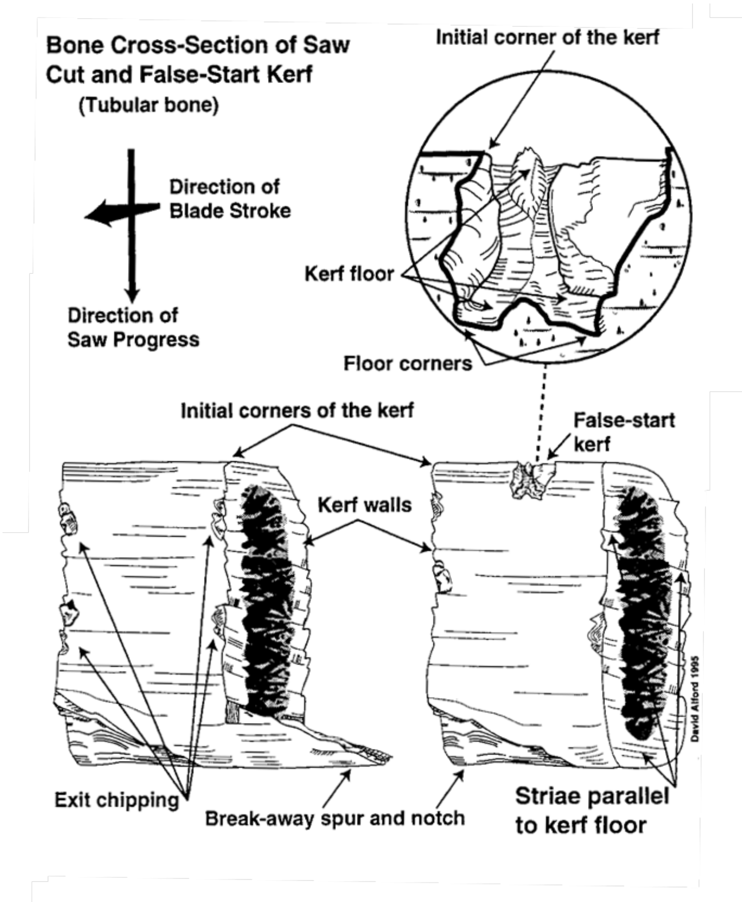

Figure 3.1: Kerf schematic diagram showing associated terminology (Taken from Symes *et al*. 1996: 393).

Cross-section shape for saw marks is designated as a class characteristic (Symes, 1992), following the trend in archaeological analysis of cut marks. On the basis of cross-sectional shape, four major classifications are suggested:

- A – Narrow kerf with rounded floor or corners. Often have one straight wall, and the other has rounded, accentuated floor corner. These are often features of serrated edged knives.
- B - Class tools may include islands of bone, floor possibly flat, steeped, or concave in the midline, according to the alignment of saw teeth. Walls are generally straight or stepped.
- C – Differs from B as the shape of the kerf floor is convex as a result of angled filing of teeth (common in crosscut saws)
- D – unique in size and undulating wall shape as a result of unique teeth.

Symes (1992) examined one serrated knife blade (with eight teeth per inch), suggesting that serrated blades saw bone well in shallow cuts, and produce features including chipping and lipping, and also describes the knife sliding from the cuts and creating scratches on the bone.

Symes *et al.* (2010) have more recently published a guide for the examination of saw marks on bone, building on the information presented in his initial study. The four cross-section classifications defined in Symes (1992) are not revisited in the later publication. Although saws can separate bone, the scope of this thesis is concerned with superficial marks. Symes *et al.* (1992, 2010) show many examples of saw mark criteria following the physical separation of bone shafts, which facilitates easier observation of features than with an intact kerf. Superficial marks that do not separate the bone are known as false starts (Symes, 1992; Symes *et al.* 2010).

Although saws and knives may be considered similar in their appearance as they can both be classified as sharp force trauma, they have very different purposes and are very different in their morphological and microscopic appearance (Symes *et al.* 2010). Saws are defined as blades with teeth, and the set of blades is said to be an important feature (*ibid.*) Set is defined by teeth that are bent laterally to a particular side of the blade, and saw blades can have a variety of set patterns (Symes *et al.* 2010) shown in Figure 3.2. It is important to note that serrated knives, though they have teeth, do not exhibit set, though knives can be considered like saws when used in a reciprocating/sawing motion such as slicing or shaving through a material (Symes *et al.* 2010).

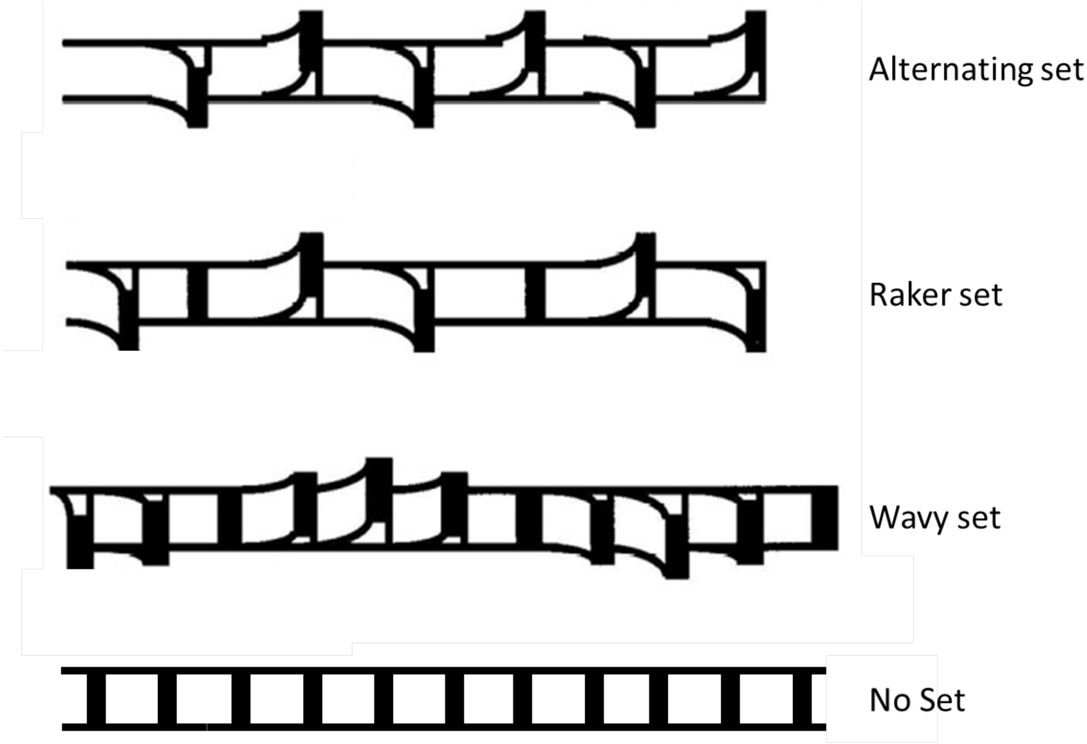

Figure 3.2: Diagram to show grades of set (cutting edge of blade viewed from above). Alternating, raker and wavy are all types of saw set; knives typically have no set (adapted from Symes *et al.*, 2010).

Many of the criteria used to distinguish between saw marks are based on differences between alternating, raker and wavy set, which is not of relevance to knife blades. There are a small number of features that could also have the potential to be applied to knife blades; floor contour, entrance shaving, and kerf flare:

- **Floor contour**: This is said to be flat in straight blade, but curved or flexible blades leave a residual curved kerf floor (Symes *et al.* 2010).
- **Entrance shaving**: Occurs as the saw enters the side of the bone, giving it a polished and scalloped appearance (Symes *et al.* 2010).
- **Kerf flare:** Flaring at the end of the cut in the floor is said to indicate the handle end of the blade as it continually enters the kerf; the opposite end of the kerf floor does not exhibit a flare (Symes *et al.* 2010).

The original work by Symes (1992) examines one serrated knife blade, and most examples of classification criteria refer to saws. No studies have explored detailed comparative characteristics of a range of metal knives visible under low power, particularly a comparison of serrated and fine bladed knives.

Symes *et al.* (1992, 2010) acknowledge that individualisation of saw marks, although the goal of the analyst, has limited potential, and the main focus is on combinations of class features for investigative purposes. Saville *et al.* (2006) studied the potential for unique or individual characteristics in saw marks. Marks were made with 40, 60 and 100 teeth in each stroke, and at angles of 45^o, 60^o, and 90^o. A subjective amount of pressure was made with three distinctions; hard, soft and intermediate pressure, and fast, medium and slow sawing speeds were used. The marks were examined using SEM, although Symes *et al.* (2010) states SEM analysis of saw marks is unnecessary and has been shown to hinder the examination. Saville *et al.* (2006) found that the kerf floor was not always useful for analysis as it was incomplete in break-away spurs, or too deep in false-start kerfs. They also measured the width of the kerfs and found that there was a great degree of overlap which makes interpretation difficult (Saville *et al.*, 2006). Three types of striations in the kerf wall were identified using the SEM, and labelled A, B and C, decreasing in size from A to C. Type C striations are highly irregular and thought to be unique to each tooth (Saville *et al.*, 2006). In blind trials, four saw operators were used to make marks with the same saws used by the authors in previous parts of the study. All marks were successfully matched to the correct saw when compared to marks made by the authors. A single operator was used to make marks with nine different saws, and when test marks were created, all marks were successfully matched. Type C striations are shown to be a robust method of tool identification (Saville *et al.*, 2006), although Symes *et al.* (2010) state that individualisation has limited potential.

The examination of saw marks provided valuable insight into a range of features suggested in order to establish weapon type from the examination of marks in bone; the kerf (cut) is defined and the walls and floor established as areas that contain characteristic features. Although knives can be used as saws, their teeth do not exhibit set, and therefore many characteristics identified by Symes

(1992) and Symes *et al.* (2010) do not apply. The experimental design of the current project (to be discussed in chapters 4 and 5) involved single entrance/exit incised wounds in bone which do not have the repetitive motion of a saw as exhibited in the above studies, and therefore the characteristics described above may not manifest in the kerf.

3.5 Distinguishing between knives and other weapon trauma using mark analysis

In addition to saw marks, establishing whether marks on bone are the result of knives, or other edged tools such as cleavers, machetes or axes has been a focus of several forensic studies, including Humphrey and Hutchison (2001), Tucker *et al.* (2001), Alunni-Perret *et al.* (2005), and Lynn and Fairgreave (2009a:b).

Macroscopic examination of hacking trauma has been undertaken by Humphrey and Hutchison (2001) and supplemented by work on the microscopic analysis of hacking trauma by Tucker *et al.* (2001). The study by Humphrey and Hutchison (2001) focuses on a different type of bone trauma (i.e., hacking rather than incision trauma), but explores a number of different observable characteristics when examining the overall morphology of the wound, and introduces data recording sheets on which to log the information. The direction and force of the blows were not controlled. Two trials were carried out; the first used fully fleshed porcine limbs held whilst the blows were applied. After maceration, marks were found to have insufficient depth for examination, and therefore a second trial involved moderately fleshed limbs lying on a flat surface whilst the weapons were applied, again without any attempt at control of force and angle. Without the use of the microscope, they were able to establish criteria that could distinguish between axe, cleaver and machete-made trauma. The characteristics observed are detailed in Table 3.1.

Characteristic	Cleaver	Machete	Axe
Entry site recognition	Clearly recognisable	Less clearly recognisable	Sometimes clearly recognisable
Entry site appearance	Clean	Clean, chattering	Clean, chattering, crushing, fracture
Entry site width	Narrow (approx. 1.5mm)	Medium (approx.. 3.5mm)	Medium to large (4-5mm)
Entry site fractures	Never	Originate past entry site - several fragments	Origins at entry site, extrend outwards, larges pieces of bone pushed into entry
Depth of Penetration	Never penetrate whole bone	Rarely penetrated whole bone	Rarely penetrated whole bone
Exit site recognition	No exit sites	Clearly recognisable	Clearly recognisable
Exit site appearance and fractures.	No exit sites	Fractures with small to medium bone fragments	Fractures with large triangular bone fragments (often singular)

Table 3.1: Summary of observed characteristics for axes, machete and cleaver marks in bone (taken from Humphrey and Hutchinson, 2001).

After consideration of macroscopic examination of hacking trauma, Tucker *et al.* (2001) build on the work of Humphrey and Hutchinson (2001) by examining microscopically marks made by the same set of instruments with the goal of identifying weapons, and, if possible, identifying a specific weapon that may have made the mark. Porcine limbs were used, with tissue removed, but some muscle and connective tissue remained. As with Humphrey and Hutchinson (2001), force was unregulated, but angles were controlled, as two marks were made at 45^{o} and 90^{o} for each skeletal element. The bones were then macerated by boiling with detergent (Tucker *et al.*, 2001). Like many of the archaeological studies discussed previously (in particular Olsen, 1988), and forensic studies by Houck (1998) and Saville et al. (2006), Tucker *et al.* (2001) casted the marks before examining them using the SEM. All of these studies used striation analysis to distinguish between weapons. Tucker *et al.* (2001) suggested the following criteria for classification of weapon hacking trauma:

- Cleaver: Fine, thin, distinct and parallel striations
- Machete: Coarse, thick and more continuous striations
- Axe: Striations not present – cut surface absent due to complete shattering of bone

Unlike Olsen (1988), Houck (1998) and Saville *et al.* (2006), Tucker *et al.* (2001) was not able to identify an individual weapon based on striation analysis, although they acknowledge that the potential for individualisation exists. Houck (1998) and Saville *et al.* (2006) both controlled the angle of interaction between the weapon and the bone, and made some efforts to control the level of force or pressure applied when using the weapon. Tucker *et al.* (2001) and Saville *et al.* (2006) both used a range of operators to apply weapons to bone; and in the case where the operators had more controlled variables, such as pressure and the amount blade interaction, more similarities were found (Saville *et al.*, 2006), suggesting that it is possible to match weapons to marks even when they are used by different operators. Tucker *et al.* (2001) failed to find features to adequately match marks with the specific weapon that made them; although different weapon operators were used, the less controlled conditions may have contributed to the greater variation of mark appearance when the same weapon was used by different people.

Further work on hacking trauma was carried out by Alunni-Perret *et al.* (2005), who found that SEM has the ability to distinguish between knife and hatchet trauma using a combination of characteristics, without including striations. Hatchet hacking trauma is compared with that made with a fine-edged knife (no other information is given) used in a chopping and stabbing motion to establish whether the weapons could be identified by the marks they made on bone. This study used a single human femoral shaft from which all soft tissues had been removed. A drop—tower was used to apply the weapons to bone to control (but not measure) force and angle. The SEM was used to examine marks directly rather than observing casts. Like Humphrey and Hutchison (2001), striation analysis is absent, with the focus instead on mark morphology. Table 3.2 lists microscopic features observed. Macroscopic features were also observed (shape, edges, and surrounding bone surface), but none were found to be useful in distinguishing between weapons; this conflicts with findings by Blumenschine *et al.* (1996) who indicated that different effectors could be distinguished macroscopically.

	Knife (n=15)	Hatchet (n=15)	Knife (n=15)
Floor	Even (15)	Even (15)	Even (10) Irregular (5)
Walls	Even (15)	Even (15)	Even (11) Irregular (4)
Edge 1	Even (15)	Irregular (15)	Irregular (15)
Edge 2	Even (2) Irregular (12)	Even (1) Irregular (14)	Even (6) Irregular (9)
Flakes (near to edge)	Flakes (12)	Flakes (14)	Flakes (11)
Lateral pushing back	(0)	(15) Bilateral (11) Unilateral (4)	(10) Bilateral (11) Unilateral (4)
Extremities	Narrow (14) Square (1)	Narrow (4) Square (7) Square or narrow (4)	N/A
Bone fragments	Present (6)	Present (9)	(0)

Table 3.2: Microscopic analysis of knife and hatchet trauma characteristic features. Observed frequencies in brackets (taken from Alunni-Perret *et al.* 2005)

Although macroscopic appearances were very similar, this study examines differences between the extremities of marks produced by the two weapon types as a result of differences in shape between the axes and the knife. Although Symes (1992) and Symes *et al.* (2010) focus on wall and floor features, Alunni-Perret *et al.* (2005) examine edges of the cut for potential diagnostic features; the first time they are documented. The walls and floor of the kerf are described as “clean”, and a unilateral raising of the cortex adjacent to the kerf is present only in the knife cut. The hatchet produced irregular edges with many surrounding fractures, as well as squared extremities. These differences are said to be distinguishable under SEM, but not using low power microscopy or macroscopic examination.

3.6 Forensic mark analysis from marks made by knives

Forensic identification of weapons from marks made in bone has been discussed in terms of saw marks and dismemberment studies, as well as comparisons with hacking implements such as axes, but there is a paucity of studies focussing on knife blades specifically and their interaction with bone; Houck (1998) looked at a small sample of three knives, Bartelink *et al.* (2001) examines three knives and Thompson and Inglis (2009) examined stab wounds using just two knife types.

Houck (1998) examined striation analysis to establish whether it was possible to identify a specific knife from the marks made on bone. This is the only forensic study to look exclusively at marks made by knives on bone. For this experiment, 105 marks were made on bovine tibial shafts by a random sample of three knife blades, using the SEM to examine the bone specimens directly. A mechanical device was used to create the marks, carefully controlling the angle and force of the blade. Marks were made directly in bone through the periosteum (the bovine shafts were sectioned and mounted before the marks were made). The blade was dropped onto mounted shaft samples, creating a chopping motion. Houck (1998) focuses on striation analysis of the marks, and no other cut mark features were explored; it was determined possible to match marks through striation analysis and thus establish whether the same weapon or type of weapon as used to make the mark. There is no indication of which specific blade types were used to make the incisions, and whether they are comparable in size and shape. As the blade is “dropped” onto the bone, the resultant mark, although classed as an incision, does not have the same dynamic action as a knife crossing the bone perpendicular to the long axis of the shaft.

Bartelink *et al.* (2001) chose to explore a single aspect of cut mark analysis for weapon identification, using the SEM, to examine whether cut mark width could be used to identify the blade. Three knife blades were used to create the marks: a utility knife, a paring knife, and a scalpel blade. A total of 20 control marks were made for each blade using a mechanical device to control force and angle, to be compared with 20 marks made manually, with no control over force or angle of the cut. The marks were then cast, and the replicates examined. This is the only forensic bone study to examine casts, rather than the mark itself directly. Analysis showed that a significant relationship exists between blade type and mark width, but the high degree of overlap between categories may result in misclassification (Bartelink *et al.,* 2001). This agrees with Shipman (1983) who also looked at this characteristic of cut marks. The blades chosen for testing in Bartelink’s (2001) study are very different, so a larger sample of blades that share more similarities may give a different result. All of the blades used in the experiment by Bartelink *et al.* (2001) have the same unserrated or “fine” edge, and the effect of blades with different cutting edge characteristics (like serrated blades) has not been addressed.

In another study, Thompson and Inglis (2009) looked at stab marks in bone rather than incised marks. Optical microscopy, SEM and macroscopic examination were used to try and establish simple classification criteria for serrated (with teeth) and unserrated (without teeth) blades. Marks were made on a rib, a radius, a scapula, a vertebra and a carpal (all elements were porcine). Bones were defleshed in detergent before the application of one serrated blade, and one non-serrated blade. The none-serrated blade is depicted as a blade with a double-ground sharp edge; there are also non-serrated blades with a single ground sharp edge; it is therefore not known how this variation in class feature would affect mark morphology; classes of serration also vary, and this is not explored as just two types of knife are represented by this study. Three marks were made with each knife blade, and examined macroscopically, with an optical microscope, and by SEM. The shape and size of the mark was recorded, and a subjective five point scale was used to assess the level of damage, with 0 equalling no damage and 5 representing extensive damage (*ibid.)*. There are no further details of the classification criteria in the method. The results tables give the classification number and details of fragmentation and fractures, but there are differing descriptions for the same level of damage classification, and some marks have no justifications for their assigned level of damage. The results showed similar trends visible at each level of magnification, with more subtle damage patterns visible at higher magnifications. On average, the serrated blade produces longer and narrower stab marks, with a higher degree of damage than non-serrated blade, The differences in mark appearance were consistent throughout all specimens and at all magnification levels (*ibid.).* The non-serrated blade produced a well-defined "T" incision surrounded by a triangular region of depressed compact bone. The serrated knife produced a "Y" shaped incision, surrounded by a triangular region of depressed bone but with a right lateral curve to the incision (*ibid.)*. The definition of the stab mark varies depending on the amount of cancellous bone present at the incision site, as cancellous bone may allow for clearer definition of the resultant mark (*ibid.)*. Greater relative quantities of cancellous bone allow for clearer definition of the mark produced (*ibid.)*. This finding could complement work by Weaver (1966) which indicated that different levels of bone hardness were measured in different skeletal elements within an individual. Changing relative quantities of cortical and cancellous bone in different skeletal elements (e.g., scapula, vertebra, radius etc.) could vary the hardness of a material. Thompson and Inglis (2009) acknowledged that their sample size is relatively small, and that marks were made with minimal soft tissue present. Further discussion on experiments and the amount of tissue present is discussed later.

Each of these studies uses a small sample of knife blades; three or fewer. Different aspects of mark identification are examined; Houck (1998) looks at striations, Bartelink (2001) examined width (morphological analysis) and

Thompson and Inglis (2009) suggested scalar examination of the level of damage in stab wounds, and morphological differences between serrated and non-serrated blades. The identification and classification of knife blades through incised wound on bone is not addressed; a more extensive range of knives needs to be examined in order to establish consistent classification criteria to enable knife cuts in bone to be distinguished according to the knife or knife type that made them. It is suggested that by reviewing the extensive archaeological literature, and the limited forensic research available in this area, this thesis can form a basis for investigation of classification criteria in incised wounds.

3.6.1 Toolmark analysis on non-bone surfaces

Whilst the analysis of knife cuts is poorly documented in the literature, tool mark identification from marks made on other surfaces is a well-established practice in forensic investigation. Burd and Kirk (1942) suggested that a mark left by the end of a sharp instrument may be sufficiently characteristic for identification, referring to marks made on wooden, metal or other smooth surfaces. Bonte (1975) established that the effect of SFT on human bone is consistent with SFT effects on inanimate materials (such as wood or metal), indicating that sharp instruments can leave recognisable traces in bone. It is therefore appropriate to apply the categories of individual or class characteristics, as used in toolmark analysis, to marks made by knives on bone.

One of the most commonly used techniques in the forensic inspection of a variety of topographical structures is light optical comparison microscopy. Its applications include the examination of general topographical features, toolmarks and deformations produced by firearms, metallic, polymeric and glass fracture surfaces (Katterwe, 1996). The successful examination of toolmarks on a range of surfaces indicates the possibility that successful mark analysis may be possible with light microscopy on other surfaces, such as bone. Prieto (1997) also acknowledges that when bone is sectioned or crossed by a weapon, it can reveal more conclusive details about weapon characteristics than soft tissue alone. Tucker *et al.* (2001) conclude that successful examination and identification of marks on bone is possible as a result of the plastic response of the organic constituents of bone, enabling cut surfaces to show evidence of the weapon edge. One of the primary purposes for comparative analysis of toolmarks is to determine whether or not two objects have been in contact with one another, or share some other class, or individual characteristics (Katterwe, 1996).

3.7 Mark Examination: Inference of Source

In archaeological, anthropological, or forensic cases, inferring the source of a mark is important for interpretation of past events. Studies have examined ways of identifying the origin of marks, or ways to distinguish between different types of effector (e.g., Sauer, 1984; Maples, 1986; Olsen and Shipman, 1988; Blumenshine *et al.* 1996; Greenfield, 1999; Humphrey and Hutchinson, 2001;Tucker *et al.*, 2001; Smith and Brickley, 2004; Alunni-Perret *et al.*, 2005; Bello and Soligo, 2008; Boschin and Crezzini, 2011). Archaeological/anthropological studies may be satisfied with identifying a broad category of what may have caused the mark, in order to interpret past processes. Forensic investigation often seeks to achieve a higher level of inference. There are a number of levels of inference in terms of relating forensic evidence (like a toolmark) to its source (i.e., the tool that produced the mark). Inman and Rudin (2001) define these levels as identification, classification and finally, individualisation. Investigators may seek answers to questions such as: “What could have caused this damage to the bone?” The forensic anthropologist might be able to form a basic conclusion such as whether the marks are a result of sharp force or blunt force trauma at the lowest level of inference (identification). Identification is defining the nature of an evidence item, without using a specific reference item (*ibid.*). It classifies materials into categories where more than one object can share the same characteristics. Classification is the next level of inference, and means inferring multiple putative common sources for an evidence item (*ibid.*). This could be as broad as concluding the mark was made by a particular type of object: e.g., a knife, a saw, a hatchet. These are extensive classifications, and investigators can explore further opportunities to exclude potential weapons; for example, the ability to establish whether the weapon (e.g., a knife) is large or small, serrated or fine, would help to exclude more potential weapons, and narrow the investigative field further. At this level it is not possible to establish from which of these potential sources (i.e., all large, fine-bladed knives) the evidence originated from. However, classification can be important for exclusionary purposes, as well as including any potential sources that may have created the evidence examined. The highest level of source inference is individualisation: that is, concluding a singular common source for evidence examined (*ibid.*). Forensic examination usually involves taking a suspect tool, or a series of potential tools, and making test marks under similar conditions as any marks found at a crime scene. The test marks would then be compared to the crime scene mark. Individualisation would be inferred if the scientist can establish that a single, specific tool was responsible for the mark, and that no other tool could have made it. Following the previous examples given, this would be the ability to establish whether the damage to the bone was caused by one specific weapon (such as the specific large fine-bladed kitchen knife found in a suspect's possession), and excluding all other large, fine-bladed kitchen knives, even those of the same make, model and size.

The methods used to establish levels of inference can vary. Identification of marks on bone for example, has been achieved by using few diagnostic criteria observed with hand lenses or microscopy at a low magnification (Blumenschine *et al.,* 1996). Classification of marks has been documented macroscopically (Humphrey and Hutchinson, 2001; Lewis, 2008, Thompson and Inglis, 2009), and by using low power microscopy and/ or SEM (Greenfield, 1999; Tucker *et al.*, 2001; Alunni-Perret *et al.,* 2006; Bello and Soligo, 2008; Thompson and Inglis, 2009; Boschin and Crezzini, 2011). Published classification criteria are limited to distinguishing between stone and metal tools (e.g. Greenfield, 1999; Bello and Soligo, 2008; Boschin and Crezzini 2011) or different weapon types (e.g. Humphrey and Hutchinson, 2001; Alunni-Perret *et al.,* 2006; Lewis, 2008; Thompson and Inglis, 2009). More examples of classification exist using microscopy (both low power and SEM); the number of characteristics observed varies – see Table 3.3. This thesis seeks to examine a larger number of characteristics than previous publications to assess their suitability as diagnostic indicators of weapon type. The types of characteristics used to define levels of inference are class, sub-class and individual characteristics.

3.7.1 Class and sub-class characteristics

The process of classification requires an ability to place the evidential material of interest into categories; it relies upon knowledge of the characteristics common to any particular class of objects (Inman and Rudin, 2001). These features or traits are known as class characteristics and are the result of a repetitive generation process, either biological or mechanical. The production of a material (such as the manufacture of a particular type of knife blade) is controlled and therefore the items that are produced during this process will share comparable class characteristics (*ibid.*). The level of similarity depends on the amount of control exerted during their manufacture. As control over the process is reduced, more differences will become apparent, and on a larger scale. Global manufacturing and mass-production has introduced the possibility of an additional set of class characteristics particular to moulds etc. that are used at a certain location; these are known as sub-class characteristics**.**

The class characteristics of a cut mark are those which may be associated with a particular group, but never a single source, such as the ability to determine that a mark on bone was made by a metal knife rather than a stone tool. Class characteristics can become more precise depending on the number of traits considered in the examination (Houck, 1998). Thus class evidence has the potential to narrow down the possible sources, depending on the number and combination of features examined. The greater the number of features that can describe a class of items, the more precise the classification can be (*ibid.*).

3.7.2 Individual characteristics

Individualisation is the ultimate goal of the forensic scientist. Individual traits or characteristics allow the scientist to narrow the number of possible to sources to one, whereas class features will always allow multiple sources, the smallest possible set being two. The process of individualisation leads to a conclusion of common source as the result of analytical similarities between two items, usually a reference sample and an evidence sample (*ibid.*). Compared items are concluded to share a common origin if they were at one time part of a whole (such as physical fit of a blade fragment recovered from the victim, and the broken knife blade, or shards of glass from a broken window), or if compared items of evidence both came from the same unique source (such as toolmarks found at a crime scene, and reference marks made with a suspect tool at the laboratory). Individual features in man-made items have been affected by manufacturing techniques. Hand-made items preclude complete uniformity; such techniques are now becoming rarer, as mass-production by machine ensures uniformity and is more economically viable. Mass-produced items are less likely to acquire individual characteristics as part of their manufacture, although hand-finishing after machining of mass produced tools may still produce such traits. Individual characteristics are acquired mostly by repeated use, wear or exposure to different environmental conditions (Rao and Hart, 1983; Rudin and Inman, 2001).

Identification and classification of weapon type from marks left in bone is of interest in archaeological and forensic fields. The highest level of inference, individualisation, is the aim of forensic investigation; however, the ability to identify such features is challenging and not always possible. When comparing reference and evidence samples, it is important to remember that class characteristics also have the potential to eliminate a significant number of potential matches. Class features can be more readily assigned, and the number and combination of features examined will affect how many samples can be eliminated or included. Documented studies look at identification and classification levels.

3.8 Summary

Unlike archaeology, in the field of forensic science, mark analysis in bone is still under development. Symes (1992) and Symes *et al.* (2010) have conducted an in depth study of saw mark analysis, relating some of their findings to serrated knives; however, the original Symes (1992) study contained only one serrated blade; the other crucial difference in many of the classification criteria proposed is that they distinguished between saw "set"; as serrated knives have no "set" (Symes *et al.* 2010), then most of the criteria are unsuitable for use with knife cuts. Thompson and Inglis (2008) carried out the first study to directly compare serrated and unserrated blade characteristics, but these applied only to stab wounds. Houck (1998) and Alunni-Perret *et al.* (2005) both applied blades in a "chopping" motion to knives using mechanical means which is different to an incised wound. Bartelink (2001) found that width could not be used to distinguish between fine blades. Houck (1998) described the potential for striations to match marks made with the same blade, which Saville *et al.* (2006) were also able to do with saws. When compared to the body of literature on archaeology, the research area needs further investigation. No studies compare features of marks made by fine and serrated blades in a larger knife samples. None of the studies measured force in order to qualify any effect it may have on marks produced. Saville, Hainsworth, and Rutty (2006) looked at the effect of operators on saw marks, but none have fully explored the effect of different operators on knife cuts. None of the studies described above have observed a detailed range of class features of knife cuts to establish whether they are related to the classification of the blade that produced them. This thesis considers all of the above features, and the next chapter explores in more detail variables considered in experimental design.

Table 3.3: Cut mark characteristics observed in previous research

			Microscopic analysis		*Observed/Suggested characteristics of cut marks*									
Authors	Date	Toolmark type	SEM	Low power	Width	Depth	Striae	Wall & Edge Morphology		Cross-section shape	Smear/ Chip/ Fault	Floor	Shoulder effect/ Barbs	Lateral Ridging
Potts and Shipman	1981	Stone	✓				✓			✓				
Bunn	1981	Stone								✓				
Shipman and Rose	1983 1988	Bone Stone	✓		✓	✓	✓						✓	
Shipman	1983 1988	Bone Stone	✓		✓		✓		✓	✓				
Bromage and Boyde	1984	Stone Bone	✓								✓			
Eickhoff and Hermann	1985	Stone			✓	✓	✓		✓	✓				
Olsen	1988	Stone Metal	✓	Hand lens			✓							
Wenham	1989	Metal	✓	✓			✓		✓					
Blumenschine *et al.*	1996	Stone Metal		✓			✓			✓				
Houck	1998	Bone	✓				✓							
Greenfield	1998	Stone Metal	✓							✓				
Bartelink *et al.*	2001	Metal	✓		✓	✓								
Smith and Brickley	2004	Stone Metal	✓		✓	✓	✓			✓				
Loe and Cox	2005	Stone Metal		✓		✓	✓	✓	✓	✓				
Alunni-Perret *et al.*	2006	Metal	✓		✓		✓			✓				✓
Bello and Soligo	2008	Metal Stone	✓		✓	✓		✓		✓		✓		✓
Tennick *et al.*	2008	Metal		✓	✓	✓	✓	✓	✓	✓		✓		✓
Lewis	2008	Metal		Hand lens	✓				✓	✓	✓	✓		
Boschin and Crezzini	2011	Metal Stone		Digital Optical Microscope	✓	✓				✓		✓		

Barbs: Sharp point facing away from the tips of incision marks as a result of involuntary hand movements by the operator (Shipman and Rose 1983)
Shoulder marks: short marks parallel to slicing mark that are inflicted at the same time, as a result of the shoulder of the tool making contact with the bone (Shipman and Rose, 1983)

Chapter 4 Experimental design considerations

4.1 Introduction

Having established the background of toolmark analysis on bone, and the need for a specific investigation which this thesis will carry out, it is now important to consider variables and factors to be taken into consideration in the design of the proposed experiment. There are no studies for direct comparison, and patchy information about factors that influence the examination and analysis of cut marks. Given the broad range of approaches applied, careful consideration is needed of each. The following sections introduce experimental variables, and provide a critique of existing publications in each aspect of experimental design.

The few existing mark classification experiments to date that include knife blades tend to examine a limited number of knife blades (often a single blade) in association with other weapon types such as hacking trauma (Alunni-Perret et al., 2005) or flint tools (Greenfield, 1999; Bello and Soligo, 2008; Lewis 2008; Boschin and Crezzini, 2011). Bartelink (2001) and Houck (2008) examined a limited set of three knives, whereas Boschin and Crezzini (2011) examine three knives in association with flint tools. The type of knife blade used in these experiments (when identified) is also restricted to a fine-edged blade, though many other knife types exist. A classification of knife blades and an introduction to the knife-blade terminology used in the rest of this thesis is introduced below.

4.2 Classification of kitchen knives

There are many different types of knife blades, but studies repeatedly indicate that kitchen knife blades are commonly used in homicides (Hunt and Cowling, 1991; Karlsson, 1998; Rogde, 2000), commonly attributed to the fact that they are readily available in most homes and easy to purchase at a wide range of outlets. For this reason this section concerns kitchen knives.

4.2.1 Blade edge types.

The knife blade has characteristic features which will be defined in this section. Common kitchen blade types are defined below (Figure 4.1):

- **Fine ground edge**– If viewed in cross section, the edge tapers from the spine to the cutting edge (Wareing *et al.*, 2008). This type of knife has a number of sub-classes; single-ground and double-ground edges.
- **Double ground edge -** the knife is ground on both edges of the blade
- **Single ground edge -** the knife is ground on only one edge of the blade.
- **Serrated edge** - A saw-toothed edge (Wareing *et al.*, 2008). The teeth tend to be narrower than those found on a scalloped edge. Usually have a greater number of teeth/points per inch (TPI/PPI). Prior to this study, there were no definitions to distinguish between serrated and scalloped blade edges. Serrated blades have 24 TPI or greater (individual teeth that are narrower than 1 mm).
- **Scalloped edge -** Similar to a serrated blade in terms of the presence of teeth. The teeth tend to be wider than those found in a serrated blade. Scalloped blades have a smaller number of TPI/PPI; where edges have fewer than 24 TPI (individual teeth wider than 1 mm) the blade can be classified as scalloped.

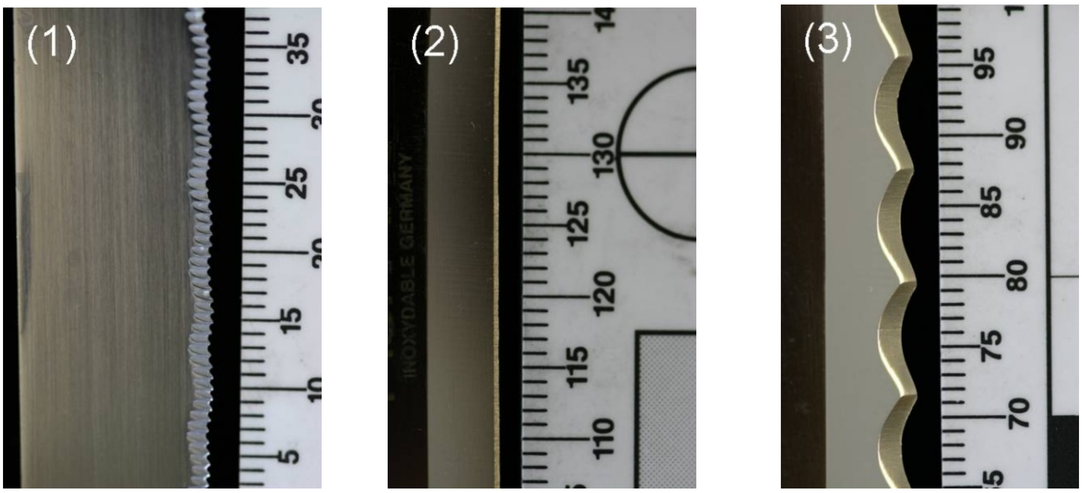

Figure 4.1: Examples of different kitchen blade edge types including (1) Serrated, (2) Fine, (3) Scalloped edges.

Tooth size is universally classified by the number of teeth per inch represented on a blade, and can be represented as teeth per inch (TPI) or points per inch (PPI). PPI values are generally one greater than TPI values (Symes, 1992).

Although there is no definitive standard for the description of knife types or blade types, the terms and descriptions shown above cover the majority of knives commonly used in homicides in Britain, and is in keeping with those used in other publications (Wareing *et al*., 2008, and see section 4.3, below), and so will form the terminology used in the current experiment

4.2.2 Knife anatomy

Although the knife blades may vary in function, shape and size, knives have a standard terminology related to their overall anatomy (Figure 4.2). Knives, irrespective of size, share a similar anatomy (Wareing et al., 2008). All the photographs shown in this section are taken by the author unless otherwise credited.

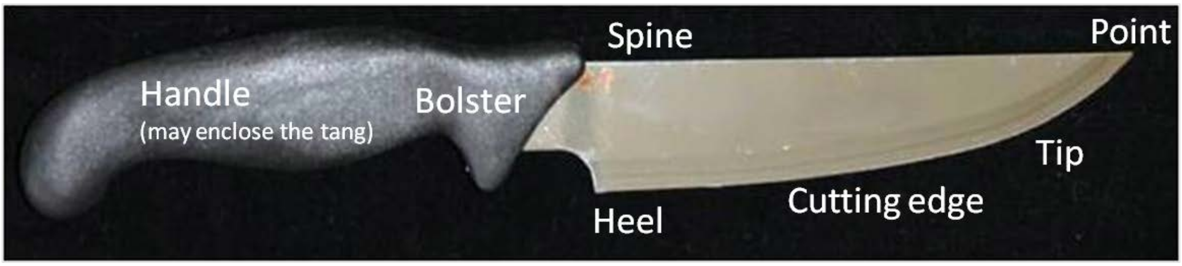

Figure 4.2: Anatomy of a knife and blade

- **Point:** Used to make fine incisions and for piercing material (*ibid.)*
- **Tip:** This is the first third of the blade, and has a fine slicing action (*ibid.)*
- **Cutting Edge:** The area of the blade that comes after the tip and before the heel (*ibid.)*
- **Heel:** The heaviest part of a large knife and closest to the hand; its original function is to be combined with strength to cleave through hard, tough, material (*ibid.)*
- **Spine:** The top of the blade; this can be wider in larger knives. Can taper and narrow towards the point (*ibid.)*
- **Bolster:** The junction between the blade and the handle, intended for protection of the fingers when the knife is used (*ibid.)*
- **Tang:** May or may not be visible; it is the part of the steel that the blade is forged from and extends into the handle. The tang may be classified as full (the full length of the handle) or half (*ibid.)*.
- **Handle:** Can be a range of shapes or materials, used for grasping during use (*ibid.)*.

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4.2.3 Knife types

There are a wide range of knives and blade types available for use in the kitchen. A selection of common knife types, categorised by the National Injuries Database (NID) or specifically mentioned in publications, are defined below (Wareing *et al.*, 2008).

Although kitchen knives have different class characteristics in terms of overall blade shape, handle shape, length and width, the cutting edge can also have a number of class features.

- **Utility knife**: Usually around 15 cm, and has a finer blade than other knives (such as the chef's knife; see blade types, below).
- **Serrated knife:** A serrated equivalent to the utility; the standard length is 15 cm (Figure 4.3)
- **Slicing/carving knife**: Has a longer, slimmer blade ranging from 18-26 cm in length (Figure 4.4).
- **Chef's knife/Cook's knife**: Has a sizable blade which ranges from between 15 cm and 36 cm (Figure 4.5).
- **Scalloped Slicer**: Approximately 28 cm in length, scalloped, though each "scallop" along the edge tends to have a shallower bevel than the standard bread knife.
- **Bread Knife**: Similar to the scalloped slicer, though there may be a deeper bevel in each scallop. (Figure 4.6).

Figure 4.3: Serrated knife blade, unbranded

Figure 4.4: Carving knife, Fiskars "Kitchen Devil" brand

Figure 4.5: Chef's knife, Fiskars "Kitchen Devil" brand

Figure 4.6: Bread knife, Fiskars "Kitchen Devil" brand

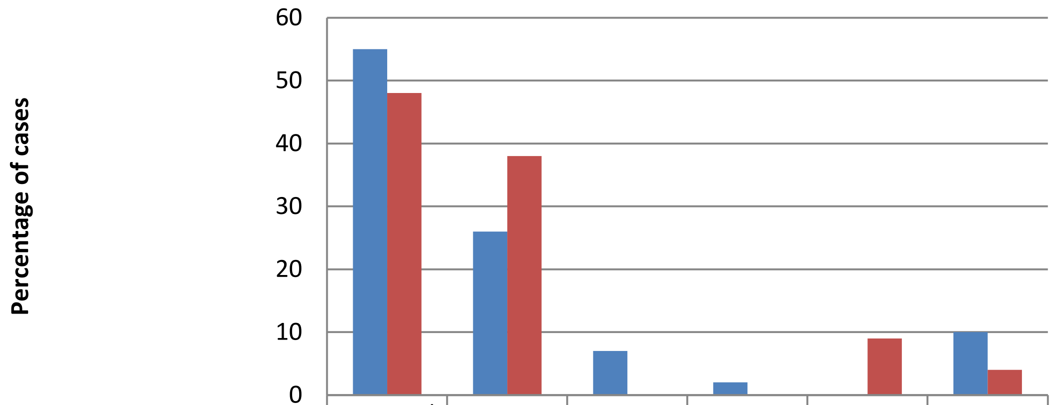
4.3 Determination of weapons used in homicides

Classification of knife blades and associated terminology is important to an understanding of how knife injuries are reported. There are a range of publications that review knife crime, weapon and injury types on a national and international scale, but previously unpublished data provided by the National Injuries Database (NID) provides a unique insight into UK homicides by sharp weapons. This data, combined with other published studies, can provide valuable information about the type of knife typically involved in homicides, as well as common injury sites. It can inform experimental design and identify variables that represent past and current trends, with the aim of making the proposed research of this thesis potentially useful to investigators. Applying for data from the NID is time and resources limited, and so the following literature research into the weapons commonly used in homicides was carried out in preparation for interrogating the database.

4.3.1 Weapon classification in published data

Hunt and Cowling (1991) detailed 100 homicides by stabbing over a 30 year period from the West of England and West Midlands areas. The most common type of knife used is a kitchen/carving knife, used in 55% of cases. This if followed by sheath knives (26%), folding knives (7%) and Bowie knives (2%). Weapons classified as “other” were not knives, but included scissors, a bayonet, a kukri (curved Nepalese knife), a samurai sword, a chisel, a sailmaker’s awl and glass (Figure 4.7). A slightly more recent study by Karlsson (1998) reviewed data on 174 homicidal deaths in the Stockholm area (Figure 4.7). Where the sharp object that caused the homicides was known (139 cases), ordinary household knives were used in 67 cases (48%). Unfortunately, the authors give no further clarification on what constitutes an “ordinary household knife”. The variation between what may be considered as ordinary household knives is illustrated in section 4.2.3. Rogde *et al.* (2000) examined 141 cases of homicide by sharp force from 1985-1994 in the Oslo and Stockholm areas. In 23% of the cases, information was available that the knife used was a kitchen utility knife. In most of the cases (no further quantification is given) the weapon as registered as a knife with no further details available (*ibid.*). Ambade and Goldbole (2006) looked at 91 SFT cases in Nagpur, India. In 68.1% of cases, the weapon was known; 66% were knives; and 22% described as stiletto knives. No further knife descriptions are provided.

Published data (Hunt and Cowling, 1991; Karlsson, 1998, Rogde *et al.* 2000; Ambade and Goldbole, 2006) suggest that kitchen knives are the most commonly used implements in homicides, although more details about knife types used are not always available. There is no clear definition of what a “kitchen knife” can be classified as across the studies; knives used in the kitchen have a range of sizes and shapes to reflect their different uses. Utility (Rogde et al., 2000) and carving knives (Hunt and Cowling, 1991) are the only two kitchen knives specifically mentioned, but the extent of the kitchen knife category is otherwise ambiguous. Kitchen knives are commonly reported as the type of knife used in homicides and therefore are the most relevant knife types to be used in the current thesis.



	Kitchen/ Carving	Sheath	Folding	Bowie	Other knives	Other Objects
Hunt and Cowling (1991)	55	26	7	2	0	10
Karlsson (1998)	48	38	0	0	9	4

Figure 4.7: Breakdown of weapon types for homicidal stabbings in the West of England/West Midlands (data from Hunt and Cowling, 1991; n=100) and Stockholm (data from Karlsson, 1998; n=138).

4.4 National Injuries Database

The National Injuries Database or NID (part of the National Policing and Improvement Agency) holds over 4,000 cases of suspicious deaths, homicides and clinical cases. It also has more than 20,000 images (www.npia.police.uk). Medical, forensic, scientific and police reports combined with photographs, x-radiographs and videos provide information for the National Injuries Database (NID). In spite of this wealth of data, the NID does not currently hold any image or information about marks on bone (Lee, pers. comm.).

4.4.1 Injury classification in the NID

The categories in the NID are focussed on the defining the injury and how it was caused, although there are no details about bone injuries. Injuries are defined by location and are categorised as: blunt; explosion; fire; firearm; physical agent; sharp/penetrating and unknown (Lee, pers. comm.) Sharp/penetrating trauma is categorised as incised, stab/puncture and defensive wounds, and the number of injuries are recorded as banded categories, ranging from a single injury to 50+ injuries (per individual) for incised wounds; the stab/puncture category has similar categories, with additional ranges recording up to 100+ injuries per person (*ibid.)*. There are also fields recording whether or not injuries are made through clothing.

4.4.2 Weapon Classification in the NID

The NID database is constructed in such a way that specific details of the weapon have to be described within the range of categories defined on the system. The first recorded details are about whether the weapon was found at the scene and if there is confirmed or suspected use. There are also fields to record whether the weapon was at the scene or brought to the scene, and whether it has been removed from the scene. The type of weapon is then categorised. There is a field for “Sharp”, which includes a “Knife” category. This is sub classified as either: knife, tool, domestic, weapon, or miscellaneous. There are a range of specific types of knives to choose from (e.g., kitchen, dining, cheese and steak, bread, boning, carving, commando, flick, etc.). In each of these weapon types, further details of the weapon can be recorded including:

- Edge type (single fine, double fine, serrated)
- Whether or not the knife is hilted
- Whether or not the knife is forked
- Blade length
- Width
- Spine width

4.4.3 NID Knife Injury Data.

Of 1019 homicide cases on the database in October 2007, 534 cases were identified by the use of a weapon categorised as “sharp knife”. Specific data about knife injuries and their locations were not available due to time restraints in interrogating the database, but data were provided for sharp instrument injuries to the chest (this includes other sharp weapons such as screwdrivers or swords). A total of 272 victims had trauma categorised in this manner (52.4%). The chest was selected as this is the area that is most commonly injured in homicides by sharp force (Adelson, 1974; Hunt and Cowling, 1991; Rouse, 1994; Rogde *et al.*, 2000; Banasr *et al.*, 2003; Webb *et al.*, 2005; Henderson *et al.,* 2005; Schmidt and Pollak, 2005; and Ambade and Godbole; 2006). There were no recorded incidences of chest injuries as a result of bread knives or cook/butcher’s knives. There were 11 cases of stabbing with a carving knife (2.1% of all sharp knife cases); 6 of those were to the chest area (Table 4.1).

Knife No	1	2	3	4	5	6
Edge type	N/C*	Single	N/C	Single	Single	Single
Length (cm)	N/C	13.97	N/C	20	21	19.2
Width	N/C	1.9	N/C	2	2.5	(spine width)

Table 4.1: NID recorded weapon data for chest stabbings with a carving knife (September 2007). N/C means no characteristics recorded.

A single case of stabbing with a steak knife is recorded, which was also to the chest area (0.19%). The steak knife had a single serrated edge, with a blade 11 cm long and 1.5 cm wide. Of 38 recorded stabbings with a kitchen knife (7.1% of sharp knife cases), 22 were to the chest (58% of kitchen knife cases). This data can be seen in Table 4.2 and Table 4.3.

Knife No.	12	13	14	15	16	17	18	19	20	21	22
Edge type	Single	Single	Single	N/C	N/C	Single	N/C	N/C	Single	Single	Not given
Length (cm)	12	N/C	22	N/C	N/C	17.8	N/C	N/C	17.8	19.7	19.97
Width	2	N/C	4.2	N/C	N/C	2.3	N/C	N/C	2.3	3.5	3.81

Table 4.2: NID recorded weapon data for chest stabbings with a kitchen knife. Knives 1-11 of 22. (September 2007). N/C means no characteristics recorded.

Knife No.	1	2	3	4	5	6	7	8	9	10	11
Edge type	Single	Single	Single	Single	Single	N/C	N/C	Single Serrated	Single	N/C	Single Serrated
Length (cm)	12	N/C	20	20	20	N/C	N/C	6.35	21	N/C	15.9
Width	17	N/C	3	3.5	3.5	N/C	N/C	1.5	2	N/C	2.5

Table 4.3: NID recorded weapon data for chest stabbings with a kitchen knife. Knives 12-22 of 22 (September 2007). N/C means no characteristics recorded

The NID provided case data that tend to support trends acknowledged by previously conducted studies (*ibid.*) discussed in section 4.3.1. In monitored homicide cases on the NID, 52.4% involved sharp injury to the chest (although this data does include tools and swords, as well as knives).

There are many publications that address the location and frequency of sharp force trauma in terms of soft-tissue injuries (Ambade and Godbole, 2006). Data describing the frequency on bone trauma as a result of sharp force trauma are less prevalent. In addition to interrogating the NID database, there are also a number of published works containing data relating to homicide by sharp force.

4.5 Injury location in homicide by sharp force

A range of skeletal elements have been used in trauma studies, and examination of homicides and injuries as a result of knife trauma provides an insight as to which areas of the body are most likely to be affected by sharp force trauma, and therefore which skeletal elements are most likely to be subject to knife wounds.

Webb *et al*. (1999) examined 120 individuals in Edinburgh (from February 1992-December 1996) who had died or received hospital treatment as a result of assault with a knife. There were 20 deaths over this study period, and as with previous studies, the chest area was the most frequently severely injured region, along with the head and neck. About 80% of deaths recorded indicated the chest was the most severely injured region; similarly, 15% involved the head and neck and 5% (a single case) involved the abdomen (Webb *et al*. 1999). In London, 62 homicides were studied that were dealt with at the St. Pancras mortuary from 1992-2001; 34 were stabbings, and of those, 80% had injuries to the trunk, and only 50% had injuries to the head and neck (Henderson *et al.* 2005). More recently, Schmidt and Pollak (2005) observed sharp force trauma injuries in 158 knife attack patients, and indicated that the least common location for sharp force trauma injury was the lower extremities (6.1%). In contrast, the thoracic area (containing the ribcage) was most frequently injured (45.9%). The suggestion that the thoracic area is a common target for stab wounds is also supported previously reported studies (Adelson, 1974; Hunt and Cowling, 1991; Rouse, 1994; Rogde *et al.*, 2000; Banasr *et al.*, 2003; Webb *et al*., 2005; Henderson *et al.,* 2005; Schmidt and Pollak, 2005; Ambade and Godbole; 2006). In spite of the wealth of literature indicating the thorax is the most targeted area in stabbings, none of the forensic publications concerned with mark analysis examine cut marks on ribs, instead examining long bones or the skull (see Table 4.4) which are much less frequently targeted.

Authors	Skeletal Element(s) used	Species
Houck (1998)	Tibial Shaft	Bovine
Bartelink (2001)	Humerus	Human
Alunni-Perret *et al.* (2005)	Femur	Human
Saville *et al*.(2007)	Femur	Porcine
Lewis (2008)	Tibia	Bovine
Bello and Soligo (2008)	Rib	Porcine
Thompson and Inglis (2009)	Rib, Radius, Scapula, Vertebrae, Carpal	Porcine
Boschin and Crezzini (2011)	Autopodia	Bovine
Shaw *et al.* (2011)	Skull	Porcine

Table 4.4: Range of species and skeletal element types used in experiments involving knives and saws applied to bone.

Previous experiments examining marks on bone have examined a limited range of knife blades, often providing little in the way of descriptions to indicate the type of blade used in the experiment. Published data (Adelson, 1974; Hunt and Cowling, 1991; Rouse, 1994; Rogde *et al.*, 2000; Banasr *et al.*, 2003; Webb *et al*., 2005; Henderson *et al.,* 2005; Schmidt and Pollak, 2005; and Ambade and Godbole; 2006), coupled with previously unpublished data from the NID, indicate that kitchen knives are the most common cause of sharp injury to the thoracic area (Lee, pers. comm). Although the NID contains categories for chef's knives and bread knives, no injuries to the chest were recorded with these knives (Lee, pers. comm). Carving knives in the NID have a separate category, and they were used only six times in 1019 cases; kitchen knives had 22 occurrences (Lee, pers. comm). The problems with the interpretation of these data arise as the definitions of knife blades across the literature seem for the most part, to be too generic. The variety of knife blades described in 4.2.3 can all be classed as kitchen knives; for the purposes of this study, a range of knives has been selected that fall under the utility and serrated category; knives of approximately 15 cm in length. Previous studies used a range of knife types and sizes (Tennick *et al.*, 2008), producing different marks. This could be attributed to a number of reasons, including blade shape, size, and the amount of force used (as force was not measured). This thesis proposes to examine knives of the same size and type, and vary only the blade pattern (fine, serrated scalloped) in order to establish whether class or individual features can be attributed to the blade. The proposed sample of 9 blades will be the largest used in a forensic experimental study of this type.

4.5.1 Bone and cartilage injury data

The data in the previous section are categorised based on soft-tissue injuries; as mentioned previously, data relating specifically to marks on bone is rare, and the NID had no records of injury to bone (Lee, pers. comm.) Banasr *et al.* (2003) carried out a study which does give a rare indication of bone injury frequencies, and the findings (although based on a very small sample of 58 cases) give a valuable and rare opportunity to compare bone injury data with more widely reported injuries of soft tissue.

Banasr *et al.* (2003) published data based on 58 fatal cases autopsied during - the period 1996-2000 (Figure 4.8). They focused on individuals who had died from stab or incised wounds; because of the low number of cases, bone and cartilage lesions are reported together. The highest proportions of these wounds were caused by knives (68.9%). A total of 31 cases (53%) presented bone/cartilage lesions, 16 of which were isolated cartilage lesions (51.6%), nine (29%) were isolated bone lesions and six (19.3%) cases showed combined lesions. In most cases the wounds corresponded to superficial or deep perforating sharp-edged cut marks, and rarely puncture marks (*ibid.*). No weapon fragments were found in the bodies examined during this study. In agreement with other published data (Adelson, 1974; Hunt and Cowling, 1991; Rouse 1994; Rogde *et al.* 2000; Schmidt and Pollak, 2005), Banasr *et al.* (2003) reported that thoracic injuries were the most common causes of death (51.6%). The ribs and sternum were involved in more than half (56%) of the bone/cartilage lesions. No bone or cartilage lesions were found in the upper or lower limbs, which is consistent with data reported by Schmidt and Pollak (2005). Although suicide and homicide cases are considered together, 54 of the study cases were homicidal in nature (Banasr *et al.* 2003). More lesions were seen in the homicide cases; even though the highest proportion of bone/cartilage lesions were found on the ribs and sternum, rib lesions were only found in homicides. The study also reports that bone/cartilage lesions were more likely to be found in cases of multiple wounds (70.9%)

The limited data on the frequency of bone injuries followed the same trend as the frequencies of soft-tissue injury. The thoracic area is the most common target, and Banasr *et al.* (2003) established that the highest proportion of bone and cartilage lesions are reported on the ribs and sternum. This thesis is novel in exclusively examining marks on ribs for forensic classification of knife cut marks; no other forensic publication examines ribs exclusively for this purpose.

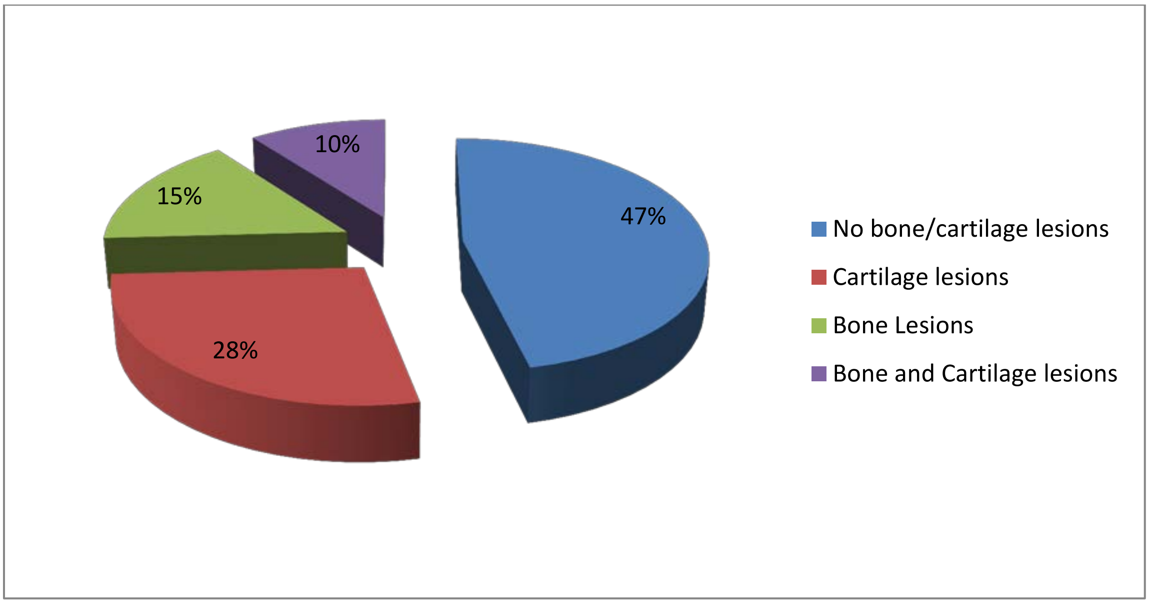


Figure 4.8: Breakdown of sharp force trauma injury location for autopsies during the period 1996-2000; Dept. of Forensic Pathology and Forensic Medicine, Garches, France (data from Banasr et al., 2003)

4.6 Replication (casting) of marks on bone

Recent work by Bartelink et al. (2001) and Sitiene et al. (2006) on width analysis for forensic identification of metal blades involved the use of casting, or replicating marks using high quality dental moulds for examination. Much of the work by Shipman and other archaeologists also used the casting approach; one of the key reasons is usually the use of the SEM, as the samples chamber size is limited, so casts must be made. Work by Rose (1983) on replication of samples using casting compounds lists some of the limitations of this form of examination. These include tendencies of the casting compound to remove very small parts of the specimen's surface (Rose, 1983), and the possibility of casting compound remaining in recesses of porous bone. She also states that specimens with small projections are more difficult to replicate accurately. The inherent limitations of this technique therefore make it unsuitable for the examination of very small cut marks, particularly when the purpose of forensic examination is the preservation of characteristics on the bone for comparison with test marks from a suspect weapon. Whilst this is appropriate when the focus of examination may be general cut-mark morphology, for forensic examination the preservation of both class (knife and blade type) and individual (one identifiable knife) characteristics that may be present in the mark is vital. Symes (1992), Tucker *et al.* (2001), Alunni-Perret *et al.* (2005), Houck (1998), Thompson and Inglis (2009), Symes *et al.*, (2010), all examine marks, including knife cuts without casting them, and are still able to establish diagnostic criteria. Use of casting is suggested only as a last resort as it may not produce a clear record of all damage features present (Barnett, 2004). Forensic analysis prefers examination, wherever possible, of the original mark.

4.7 Cut marks and experimental surface media

4.7.1 Bone

The use of porcine bone as a model for human trauma is an appropriate substitute, as non-human mammalian bone is considered to be a suitable medium for this type of experiment (Maples, 1986; Houck, 1998). Recent forensic studies have used mammalian lower-limb bones as a cutting medium (Houck, 1998; Tucker *et al.*, 2001; Alunni-Perret *et al*., 2005; Lewis, 2008). Although bovine bone is used in some of these studies, Bromage and Boyde (1984) noted that the use of cow bone as an experimental substrate affected results because the bone tissue type is prone to the production of oblique chips; this may affect any morphological assessment of cut marks and therefore impacts on their suitability as a substitute for human bone. Saville *et al.* (2006) carried out tests comparing human and animal bone in relation to saw marks and found that pig femora showed the same types of marks as human bones when cut. The presumption by Bromage and Boyde (1984) is that the mark morphology was constant because experiments were based on one bone or one type of bone (Bromage and Boyde, 1984). Rho *et al.* (1998) suggest that in cortical bone the mechanical properties are influenced greatly by the porosity, mineralisation and the organisation of the solid matrix. Eickhoff and Herrmann (1985) suggested that the bone surface influenced variation within cut and tooth marks observed on bone. Weaver (1966) and Saville *et al*. (2006) had examined hardness of bone as a variable. Although hardness is not measured in the current thesis, the findings indicate that porcine bone has the greatest similarity to human bone in terms of hardness; Weaver (1966) looks at differences within and between individuals; the same skeletal element in different individuals may have similar levels of hardness, but elements within the same individual may show a greater variation. Studies that have used a wide variety of skeletal elements (many of the archaeological studies, e.g., Potts and Shipman, 1981; Bello and Soligo, 2008) and some of the forensic studies (Humphrey and Hutchinson, 2001 and Tucker, 2001) may show variations in the marks made based on the hardness of a femur and a tibia for example, as well as variation as a result of the bone surface, and possible variation based on the type of species used.

4.7.2 Bone Hardness

Hardness can be classified as the resistance of a material to penetration (Weaver, 1966). The size of the impression is proportional to the size of the penetrating load and inversely proportional to the hardness of the test material (*ibid*.).

Examination of marks at a crime scene may be on surfaces such as a metal window frame or door catch-plate. The elastic properties of bone, and its honeycomb structure, will vary from those of metallic surfaces (*ibid.*). Studies were carried out on those variables which might affect the microscopic hardness of human bone (*ibid.*) Weaver (1966) states that the rapid freezing and storage of bone at -20 degrees centigrade in a sealed container had no appreciable effect on cortical hardness provided the surface to be tested was prepared freshly (*ibid.*). It was also found that hardness measured in specific sites on the fibula, tibia, and ulna within an individual varied widely, but there was very little variability in the hardness of the same bone from standard sites in different individuals (*ibid*.). Saville *et al*. (2006) carried out hardness testing on a number of animal bones, including a pig femur and tibia, a bovine femur, a cervid tibia, and an ovine femur and tibia. These bones were then compared against the right femur of a 74-year old human male. Animal bones showed greater variation in hardness values and the difference is attributed to bacterial degradation leading to a softening of the bone (Saville *et al.,* 2006). It is not clear why this effect is exclusive to the animal bones; it may be the human femur has undergone some form of preservation treatment, but this is not explicit in the methodology; indeed, if this is the case then any treatment may have affected the hardness values. Saville *et al.* (2006) found that pig bone had a comparable hardness to the human bone and therefore continued to use porcine bone in saw mark experiments.

4.8 Presence of soft tissue

Recent studies (Houck; 1998; Alunni-Perret *et al.*, 2005) made marks directly onto bone through the periosteum. The importance of the presence of soft tissue as a shield from stone and bone tools was noted by Shipman and Rose (1983: 86), but the effect of different soft tissue thicknesses on marks made by metal blades has also been investigated. Lynn and Fairgreave (2009a) examined hacking trauma made on fleshed and unfleshed porcine specimens, and found that defleshed bone was more easily bisected, with fewer blows. This was attributed to the flesh absorbing some of the energy of the impact. It is also suggested that the absence of flesh could result in features characteristic of marks made by a higher force in defleshed bones (Lynn and Fairgreave, 2009b). The weapons used in this study were axes and hatchets, which tend to be heavier and as a result, they apply a different range of forces than knife blades (Lynn and Fairgreave, 2009a). The overall shape and size of the weapon may also have an effect. Knife blade force has been examined by a number of researchers; Knight (1975) stated that skin is the most resistive tissue, but once a knife penetrates skin, no further force need be applied. O'Callaghan *et al.* (1999) confirmed that skin has the highest resistance, with muscle showing a smaller a resistive force. However, it is concluded that resistance of underlying tissue is easily overcome by an assailant performing a stabbing action and it is inconsequential in such cases (O'Callaghan *et al.,* 1999). The experiment undertaken by O'Callaghan *et al.* (1999) stabbed through 10 cm of skin, muscle and subcutaneous fat; in spite of this finding, work by Shipman and Rose (1983) and Humphrey and Hutchinson (2001) indicated the presence of the periosteum, and more additional tissue on the bone, can have an effect on depth to which weapon marks penetrate the bone; however, neither of these studies measured force when creating the marks. Gilchrist *et al.* (2008) examined the penetration of knives using a skin simulant, and found that on testing four knife types (cooks, utility, carving, kitchen) the utility knife required least energy to break the skin simulant, and the cooks knife required the most energy. The tests were carried out at a relatively low speed and it was acknowledged that further work should be carried out at speeds more representative of a human stabbing action. The results indicated that the knife type may have an effect on the level of force required to penetrate human skin (*ibid.*).

4.9 Application of implements to experimental media (force)

Humphrey and Hutchinson (2001), Tucker *et al.* (2001), and Lewis (2008) apply weapons to their subjects manually, with no control over force and angle. The justification is given that most traumas inflicted and subsequently examined in forensic casework would be unregulated (Tucker *et al*., 2001). Other authors (Houck, 1998; Bartelink *et al*., 2001; Alunni-Perret *et al*., 2005, Shaw *et al.*, 2011) with interests in the forensic principles of cut mark analysis used mechanical application of knife blades in order to replicate marks, but these mechanical applications may result in artificial levels of similarity.

4.9.1 Force measured trials – human operators

The kinematics of a number of stabbing methods was experimentally recorded by Miller and Jones (1996). A small sample of ten subjects (all right-handed) was required to stab a target, and the speed and velocity of their movements was measured using video software. Four different stabbing methods were demonstrated and involved varying the distance of the subject from the target as either “long” (1.25 m) or “short” (0.5 m) as well as varying the method of holding and moving the knife. The knife was applied using an overhand stroke (whereby the blade of the knife emanated from the ulnar aspect of the hand), or an underhand stroke (when the knife blade emanated from the radial aspect of the hand). The results showed that the distance from the subject and the way in which the knife was held influenced the maximum potential speed that can be generated during stabbing. The force of the blade was not measured, but if the speed is affected by these variables, it is reasonable to assume that it is possible the force applied to a target could also be affected and illustrate the potential variation that could be introduced by the person using the weapon on a stationary target. This is also demonstrated by Horsfall *et al.* (1999), who examined a range of human subjects using overarm (n=46) and underarm (n=157) stabbing actions against a stab-proof target. It highlights the variation in performance (force and impact energy) between subjects, and the significantly greater energy applied by male subjects than female subjects. In another study conducted by Horsfall *et al.* (2005), the effect of knife handle ergonomics on stabbing armoured targets is examined. Four handle variations were tested and found to have slight effects on the impact energy measured. As with the previous study, the greatest variation was a result of the participants in the study.

4.9.2 Force measured trials – human operators and mechanical apparatus

Chadwick *et al.* (1999) carried out comparative experiments in a series of 20 volunteers and drop-tower tests (a mechanical apparatus with a blade attached) stabbing a target consisting of simulated flesh covering a stab resistant material, and observed that measurable differences in energy, momentum and velocity existed between the mechanical technique and the manual volunteers. In the human stab, the energy and momentum measured are made up of a number of different masses travelling at different velocities, and the mechanical drop-tower has only one mass in motion, which appears to be a limitation of using mechanical equipment when considering blade penetration as a variable (Chadwick *et al*., 1999). Marks made manually that show similar features may have greater significance in practical application, as marks examined in the field could be subject to greater variation. This is supported by findings that show the angle of the blade has a statistically distinguishable effect on the cross-sectional appearance of a cut mark (Lewis, 2008). Bartelink *et al.* (2001) also found that blade stroke force and angle dramatically influenced the width of the cuts produced. Shaw *et al.* (2011) examined two knife blade types that had different angles of grind on the blade. The study used a drop-tower approach, similar to Alunni-Perret *et al.* (2005), and the knives were dropped onto pig skulls that were fixed to a steel plate by polyester resin. The impulsive energy of the knife was calculated according to its gravity force. The knives were dropped from four different heights; 19.6 cm, 44.1 cm, 78.4 cm and 122.5 cm. An optical microscope was used to create images and 3D composite images of the marks, as well as take measurements. A higher external force resulted in a deeper cut (Shaw *et al.*, 2011). However, these findings were based on a comparison of only two knives, each making four marks (according to tabulated data) (Shaw *et al.* 2011).

4.10 Cut mark classification

The cross-disciplinary study of cut mark analysis to date has a lack of consistent, descriptive and accurate terminology (Symes *et al*., 2002), which this thesis aims to address. Published criteria for identification of metal cut marks vary in detail and their purpose for discrimination. Little research exists in determining identification of different metal blade types, whereas many different characteristics have been identified for establishing differences between cut marks and percussion pits, or scavenger tooth marks (Blumenschine *et al*., 1996; Loe and Cox , 2005), as well as distinguishing between different types of metal weapons (Wenham, 1989; Lewis, 2008), and modern forensic studies examining blade characteristics of different weapons (Houck, 1998; Bartelink *et al*., 2001, Thompson and Inglis, 2009). It was therefore necessary to review the available literature across a range of subjects in order to identify the depth and nature of observations made by others.

4.10.1 Kerf features and cut mark vocabulary

Symes (1992) designated the channel or groove made by the action of a blade on the surface as the kerf (Figure 4.9). This term was initially used in reference to saw marks, but was also later applied to knife marks (Symes, 2002, Symes *et al.* 2010). Symes (1992) also defined the kerf "walls" and "floor", and for saw mark analysis suggests that the walls and the floor must both be examined. Kerf characteristics for knife blades are not clearly documented, or consistently assessed in the literature.

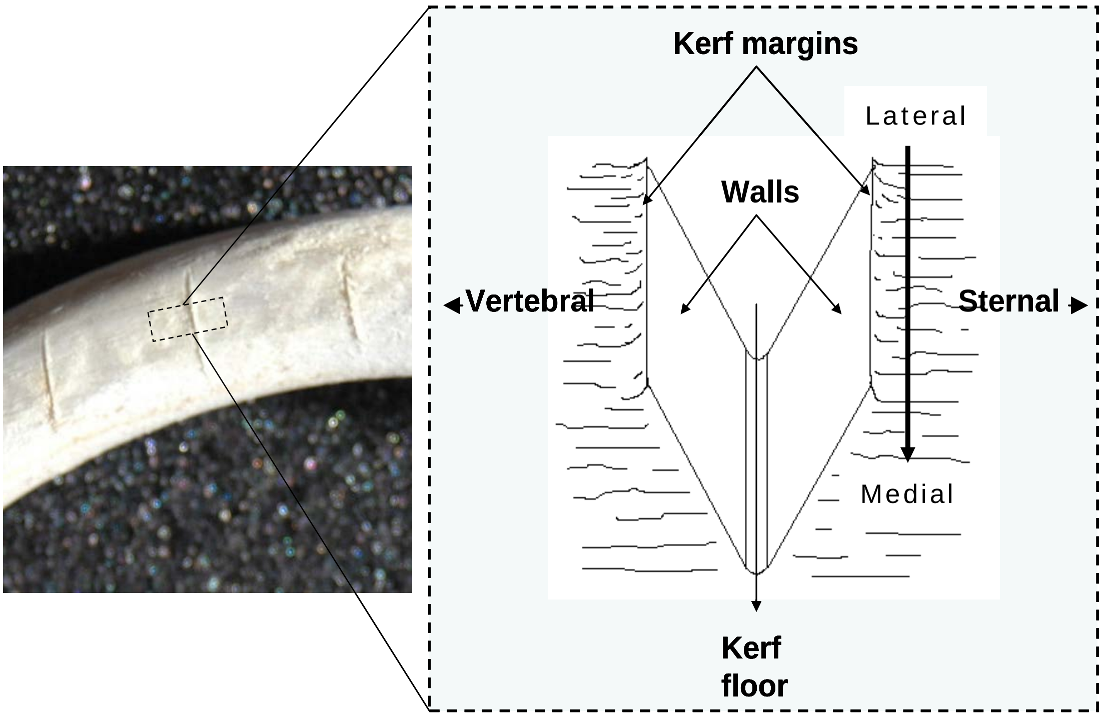


Figure 4.9: Photograph showing serrated incisions on bone with a schematic representation of the kerf

Table 3.3 shows the variation in kerf features examined or observed across a number of disciplines, and a number of methodologies are discussed in previous sections. Loe and Cox (2005) review a comprehensive range of mark characteristics; however, these refer to striations on bone that do not specifically describe cut marks alone. Lewis (2008) examines eight traits including cut mark length, shape, feathering, flaking, cracking, breakage, bone shards and angle of entry; this allows differentiation between knife and sword marks on bone (*ibid*.). Bello and Soligo (2008) use six classification criteria to distinguish between knife marks including:

- The angle between the slope of the cut mark and the uncut bone surface
- Opening angle of the cut mark (the angle between the walls at the floor)
- Bisector angle
- Shoulder heights (heights of shoulders formed at either side of the cut)
- Floor radius
- Perpendicular depth of cut

Here, rather than examining morphological traits, Bello and Soligo (2008) use qualitative data. The opening angle of the cut mark describes the floor of the kerf and will be relative to the overall cross-sectional shape. The "shoulder heights" described in this paper seem to be equivalent to "unilateral raising" features documented by Alunni-Perret *et al*. (2005). This feature is different from the similarly named "shoulder effect" described by Shipman and Rose (1983), which is a secondary mark alongside the main toolmark, rather than "raising" (Alunni-Perret *et al*., 2005) or "shoulders" (Bello and Soligo (2008) at what Lewis (1998) would term the "sides" of the kerf, and Alunni-Perret et al (2005) would call kerf "edges".

The striation ("kerf") characteristics may also be used to describe chopping and scraping marks on the surface of bone (Loe and Cox, 2005). The use of the term "striation" in this context is not to be confused with the internal striations inherent within a mark as the result of the cutting action of the tool against a hard surface (Burd and Greene, 1948), again illustrating how disparity in terminology across subject areas exists. Kerf features described in the literature to date is summarised and described below.

4.10.2 Cross-section profile

Cross–section shape has been examined by a number of authors, in archaeology to distinguish between metal blades and other effectors such as stone/bone tools (e.g., Potts and Shipman, 1981, Shipman, 1983, Greenfield, 1999) or toothmarks (Blumenschine et al., 1996) as well as by Symes (1992) and Symes *et al.* (2010) in the examination of saw marks. It has not been examined as a potential classification criterion in a large sample of knives, and studies, with the exception of Thompson and Inglis (2009), have focussed on fine blades. Symes (1992) describes the characteristics of a single serrated blade in a sawing motion but serrated cross-section profiles have not been described as a result of a single incision mark on bone.

4.10.3 Aspect (angle of entry)

Lewis (2008) looked at the angle of entry of the weapon but did not discuss its use as a criteria for classification; Bello and Soligo (2008) inferred angle of entry by looking at other criteria examined, and Alunni-Perret *et al.*(2005) acknowledged the angle of entry as a variable that caused variation in marks examined.

4.10.4 Extremities

These are the kerf peripheries; Alunni-Perret *et al.* (2005) compared their shapes and found them useful to distinguish between hatchet trauma and knife trauma; Symes *et al.* (2010) also describes features including entrance shaving, which gives the bone a polished, scalloped appearance, or kerf flare, when the end of the cut has a flared appearance, said to occur at the handle end of the blade.

4.10.5 Mark dimensions

Length was examined and found not to be useful for classification between sword marks, although knife marks were shorter than the sword marks. The length was thought to relate more to the diameter of the bone than the weapon itself (Lewis 2008). Analysis of cut mark width showed that a significant relationship exists between blade type and mark width, but the high degree of overlap between categories may result in misclassification (Bartelink *et al.,* 2001), agreeing with archaeological studies by Shipman (1983).

4.10.6 Cut mark shape

Humphrey and Hutchinson (2001) looked at hacking trauma but commented on the overall wedge-shape of marks in bones made by axes as a diagnostic class feature. Lewis (2008) defined features to distinguish between different sword types and a single type of knife by looking at the overall shape of the mark.

4.10.7 Wall features

Loe and Cox (2005) refer to wall slope to distinguish between stone and bone tool use; Bello and Soligo (2008) look at the "angle of slope" and infer that this can be used to establish the angle of tool application, and potentially handedness, but only if the direction in which the cut was made is known.

Wenham (1989) discussed how sword marks left linear marks with a cut bone surface that is flat and smooth, and possibly with a polished appearance. Lewis (1998) describes the walls themselves in terms of their relative heights and their level of damage, e.g., whether they are smooth, roughened or damaged. (Alunni-Perret *et al*., 2005)

4.10.8 Edge Characteristics

Features around the edges or margins of the mark were described by Shipman and Rose (1983) in terms of "shoulder marks"; the result of the shoulder of a stone tool moving across the surface of the bone. "Barbs" *(ibid.*) were described as hook shaped features at the termini of the cut mark, and were thought to be caused by involuntary movements of the operator as they applied the tool to the bone surface. Wenham (1989) referred to well-defined edges and a linearity of the mark being diagnostic of marks made by an edged weapon. Alunni-Perret *et al*. (2005) refers to "lateral raising"; Bello and Soligo (2008) refer to "kerf shoulders". These seem to be equivalent vocabulary to describe raised features at either or both margins of the kerf, and in both cases seem to indicate more about the angle of the weapon as it impacts the bone rather than giving any class indications about the weapon that created the associated mark. Lewis (1998) refers to the edges as "sides", and focuses more on the discussion of damage to the sides than any other features.

4.10.9 Floor Characteristics

Bello and Soligo (2008) examined the radius of a circle fitted to the floor of the cutmark and found that it could distinguish between stone and metal tools as a result of a longer radius in stone tool cuts and more variation in measurements taken in stone tool cuts than in knife blade cuts. Symes *et al.* (2010) describes floor contour for saws - flat or curved to reflect the shape of the saw.

4.10.10 Debris Characteristics

Crushing has been noted as a characteristic of bone tools (Potts and Shipman, 1981, Shipman, 1983), tooth marks (Blumenschine *et al.*, 1996) and certain types of hacking trauma (Humphrey and Hutchison, 2001). Flaking has been described as a feature of hacking trauma and sword injuries (Wenham, 1989, Alunni-Perret *et al*. 2005, Lewis 2008). Feathering is described as “wispy” (Lewis *et al.*, 2008) damage to the sides or edges of a cut mark; in knife marks this was found to sweep laterally in the direction of the cutmark and is useful in determining the directionality of a stab (*ibid.).* Types of trauma such as broken bone and cracking are also suggested by Lewis to be useful in assisting classification of sword type.

In summary, it can be seen that there is a wide variety of terminology, descriptions and foci in the literature concerning this area of study, and moreover, there is no agreed standard for vocabulary or methodology. Both archaeological or forensic studies of cutmarks have discussed a variety of features, with a range of potential uses. The most current studies (Lewis, 2008; Bello and Soligo, 2008) have objectives centred around archaeological interpretation and look at a limited number of features. Others, such as Bartelink *et al.* (2001) and Alunni-Perret *et al.* (2005) highlight particular features and discuss them in detail. There is to date no focussed work on knife blade classification that considers a broad range of morphological characteristics and their potential for forensic and knife blade classification or identification using optical microscopy. Many publications address differences between distinct classes of weapons such as knives and hacking weapons (e.g., Humphrey and Hutchinson, 2001, Tucker *et al*, 2001, Alunni-Perret *et al,* 2005) or knives and swords (Lewis, 2008); the ability to reliably identify or classify knife blade marks on bone using a technique as widely available and economically viable as optical microscopy has great appeal for investigators.

4.11 Microscopy

Scanning electron microscopy (SEM) has been widely used for the identification of marks on bone (Shipman, 1981 *et al.)* in archaeology and to a lesser degree in forensic science (Humphrey and Hutchinson, 2001, Tucker *et al*. 2001, Bartelink, 2001, Saville *et al.* 2006, Lynn and Fairgreave 2009b). However, the nature of the SEM prohibits direct examination of many specimens, and therefore the marks are required to be cast for examination. The costs and time involved in examining large collections are prohibitive both in archaeology, and in forensic investigation, where police forces and laboratories are now required to carefully consider the necessity of certain types of examination, and assess prudently the costs associated with a method of examination against the likelihood of obtaining useful evidence to assist in the investigation. Symes *et al.* (2010) states that SEM analysis is unnecessary for accurate analysis of saw marks on bone, a view shared by Blumenschine *et al.* (1996), who examined macroscopic analysis against optical microscopy and demonstrated that class characteristics have the potential to be successfully observed using optical microscopy, and used diagnostically to distinguish between mark effects on bone. Optical microscopes allow easy manipulation of full specimens, unlike SEM, and samples have the potential to be processed quickly and accurately, as demonstrated by Blumenschine *et al.* (1996). Samples require less preparation (no need for sectioning or sputter-coating), reducing costs and turnaround time for analysis.

This chapter has examined in more detail some of the key considerations in experimental design, including the basis for using optical microscopy, the choice of weapons and skeletal material, the rationale behind force measurement and the kerf observations used as the basis for classification criteria. The next chapter describes the experimental method in detail.

Chapter 5 Materials and Methods

5.1 Introduction

Although aspects of the following methodology have been adapted from existing literature, the combination of factors measured and analysed is novel, and new terminology is introduced.

5.2 Knife samples

The dictionary definition of a knife is “a cutting instrument, consisting of a blade with a sharpened longitudinal edge fixed in a handle, either rigidly (such as a carving knife), or with a joint (pocket knife) (OED, 2012). *The Knives Act* 2007 gives a much broader definition as “an instrument which has a blade or is sharply pointed”.

This experiment was designed to ascertain whether cut marks in bone exhibit features related to the type of knife that made the mark, and whether these features could be identified in marks made by a variety of different operators using the same knives.

Nine knives were selected to create the incision marks on bone. The knives used are all classified as utility/serrated blades (Wareing *et al.*, 2008), with comparably similar blade lengths and shapes. The utility knives were all purchased from kitchen departments in Preston stores and could be considered as ‘kitchen knives’. These knives were selected on the basis that kitchen knives have, to date, been the most commonly used implements in sharp force trauma (Adelson, 1974; Hunt and Cowling, 1991; Rouse, 1994; Webb et al., 1999; Rogde et al., 2000; Banasr et al., 2003; Henderson et al., 2005; Schmidt and Pollak, 2005; and Ambade and Godbole; 2006), although no formal definition exists. The kitchen knives belonged to three classes according to their blade type; fine, scalloped and serrated. Figure 5.1 and Figure 5.2 show the knife subgroups and further characteristics.

5.2.1 Knives: Class features

The purpose of selecting knives with particular class features was to test the level to which cut marks might reflect the class characteristics of the tool. In addition to distinguishing between different blade groups (class features) it would be of more value to the forensic investigator if knives within a particular class group could be identified (sub-class features). In the knife groups, each class was represented by 3 blades. Further sub-class characteristics of each blade are described below and have been tabulated (Table 5.1). A summary of the sub-class differences within each class is described below.

- **Fine class (1-3):** This class had the most similar blades; the differences were subtle; the blade cutting edge length, shape differences at the tip were the key differences between these blades.
- **Scalloped class (4-6):** The number of teeth per inch (TPI) varies, as well as the tooth height. There were also subtle differences in the shape of the blade tip and the length and shape of the short, fine ground edge at the tip, present in each knife in this class,
- **Serrated (7-9):** TPI, tooth height, blade tip shape and the length of the fine ground edge presented at the tip all show variation within the serrated blade class.

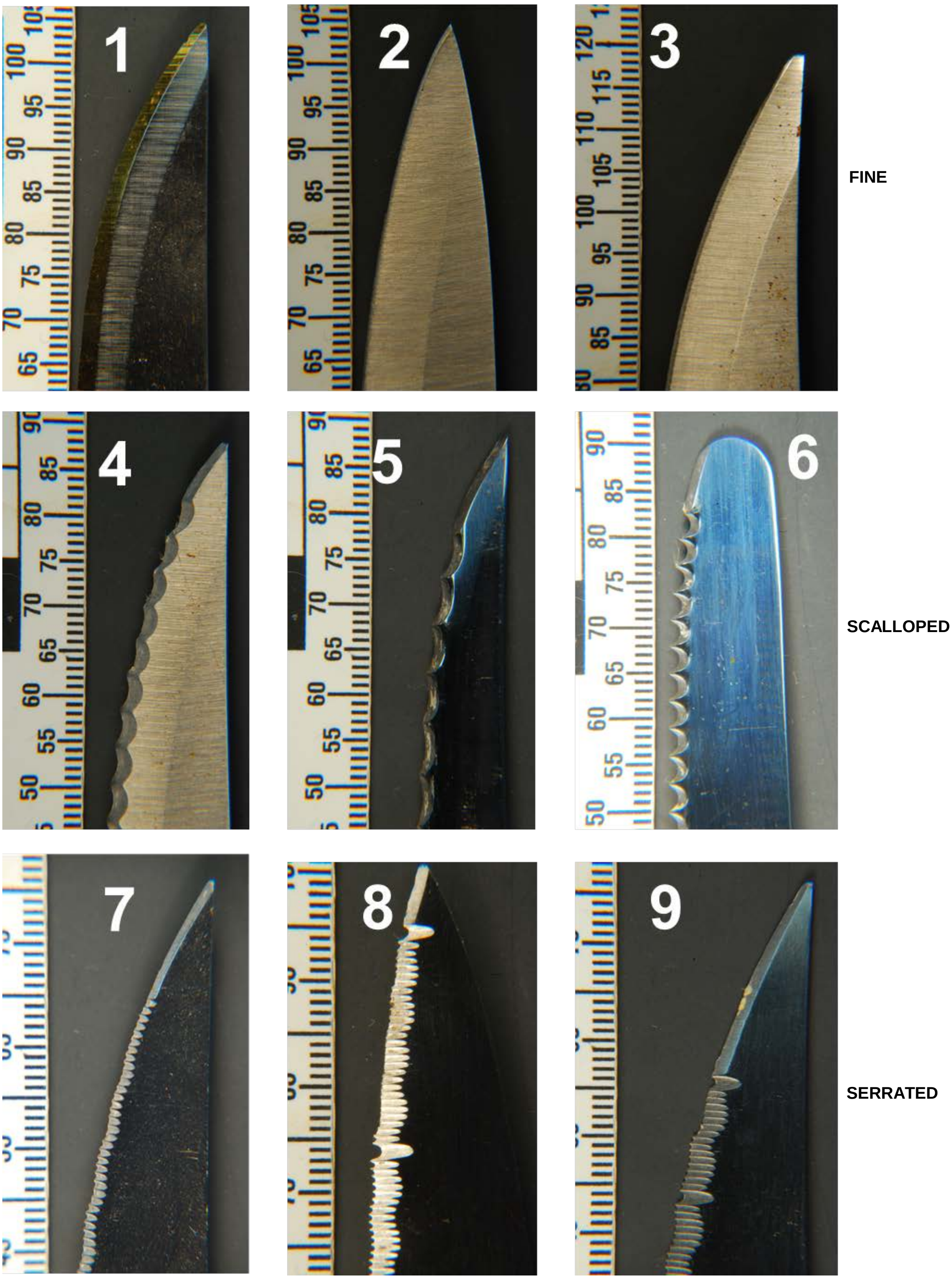


Figure 5.1: Sample blade classes: 1-3 Fine, 4-6 Scalloped, 7-9 Serrated.

Figure 5.2: Knife sample set of utility blades. 1-3 are fine-edged, 4-6 are scalloped-edged, and 7-9 are serrated-edged blades.

Each blade was new at the time of purchase. Prior to use each knife was examined using the Leica S60E Transmitted Light Stereomicroscope at x40 magnification in order to establish the class features of the blades, after Symes (1992). The following characteristics of each side of the blade were documented:

- **Number of teeth per inch** (TPI) and **total number of teeth in the blade** (Symes 1992): This was useful for distinguishing between serrated and scalloped blades.

- **Total tooth height**: Measured at one tooth from each of the following locations: blade tip, handle and midpoint. This was the height of the tooth from its apex, to a baseline between the two points of the tooth (labelled (a) in Figure 5.3).

- **Height of the tooth**: Cutting edge was measured at one tooth from each of the following locations: blade tip, handle and midpoint. This was the height of the cutting edge of the tooth, measured centrally in the tooth, and shown as (b) in Figure 5.3.

- **Total blade length** (Symes, 1992): The blade of the knife was measured from the tip to the handle, including the sharpened part of the cutting edge and any unsharpened part towards the handle.

- **Cutting edge length**: The sharpened cutting edge length.

- **Length of patterned edge**: The sharpened length of the cutting edge that demonstrates any form of tooth pattern.

- **Length of unpatterned edge**: The sharpened length of the cutting edge that demonstrates no pattern; a fine ground edge.

- **Width of spine at blade handle**: Width of the blade at the back (spine) of the knife, adjacent to the handle; this is the widest part of the blade.

- **Width of spine at blade tip:** Width of the blade at the tip – usually the narrowest part.

- **Presence/absence of bevelled edges and their location**: The numbers of bevels were noted, and which side of the blade they were present on.

- **Location of patterned/sharpened edges:** Described whether the blade is patterned/sharpened on one or both edges.

All width measurements were made using a “WorkZone” electronic sliding callipers.

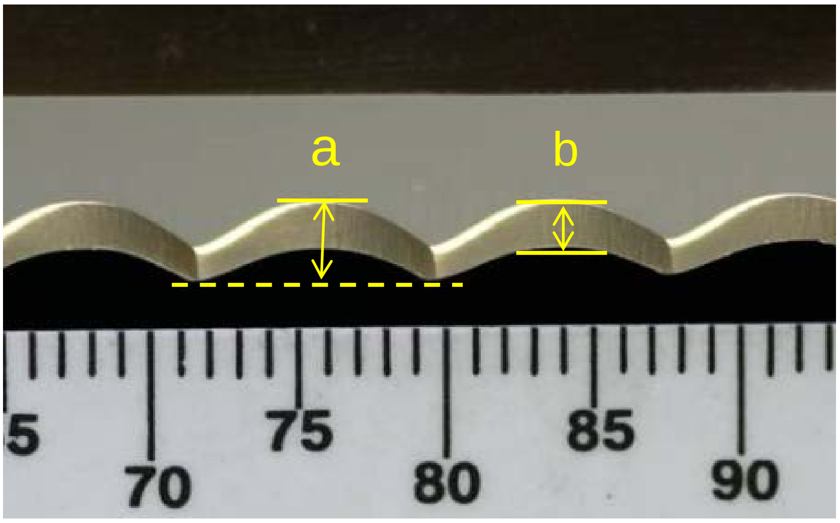


Figure 5.3: A patterned scalloped blade. Total tooth height is measured between the points illustrated under (a), and edge height is measured by the points illustrated under (b).

Knife No.	Knife code	Blade Type	Manufacturer	Tooth frequency. Teeth per inch (TPI)	Total no. Teeth	Total blade length (mm)	Cutting edge length (mm)	Patterned length (mm)	Fine length (mm)	Spine width (blade handle)	Spine width (blade tip)	Right bevel	Right cutting edge	Left bevel	Left cutting edge
1	**F1**	Fine	Wilko	N/A	N/A	130.3	125	N/A	125	1.4	0.89	Multiple (2)	Fine	Multiple (2)	Fine (gold –coloured titanium coated edge)
2	**F2**	Fine	Prestige	N/A	N/A	118	114	N/A	114	1.1	0.42	Multiple (2)	Fine	Multiple (2)	Fine
3	**F3**	Fine	Pro Blade	N/A	N/A	135	120	N/A	120	1.5	0.40	Multiple (2)	Fine	Multiple (2)	Fine
4	**SC1**	Scalloped	Prestige	6	23	115	100	95	5	1.14	1.14	Single	Patterned (points only)	Single	Patterned (scallop)
5	**SC2**	Scalloped	Kitchen Craft	4.5	17	120	105	95	10	1.96	1.15	Single	Patterned (points only)	Single	Patterned (scallop)
6	**SC3**	Scalloped	Swan	9	31	110	100	93	7	0.95	0.88	None	Patterned (points only)	None	Patterned (scallop)
7	**SR1**	Serrated	Unknown	25	106	114	100	85	15	0.73	0.77	Single	Patterned (points only)	None	Patterned (serrations)
8	**SR2**	Serrated	House and Home	27	135	115	110	105	5	0.91	0.84	Single	Patterned (points only)	None	Patterned (serrations)
9	**SR3**	Serrated	Laser (Richardsons of Sheffield)	30	105	123	110	85	25	0.9	0.49	Single	Patterned (points only)	None	Patterned (serrations)

Table 5.1: Class and sub-class characteristics of utility knife blades used.

5.3 Bone for modification

Specimen porcine ribs (*Sus scrofa*) were chosen as a suitable medium on which to make the marks and were obtained from a Preston commercial butcher as articulated (Figure 5.4).

Figure 5.4: Example of ribs for examination

5.3.1 Preparation

The ribs were separated by severing articulating vertebrae, and ensuring that the rib surfaces remained unaltered. This resulted in individual ribs, each remaining articulated with corresponding vertebrae.

The ribs were checked for pre-existing marks. The rib was visible at the sternal end, and measurements of adhering tissue at the sternal end were taken for superior, inferior, medial and lateral surfaces,[1].

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[1] Although pig ribs were used, orthograde (trunk-upright) directional terms have been applied, as this is a model for human trauma.

The ribs were also weighed prior to maceration in order to give a proportional indication of the amounts of tissue on each rib.

As several sets of ribs were utilised and individual ribs varied in width, length, and cortical thickness, each rib was allocated a code identifying anatomical rib no and the animal from which it came. The anatomical location and individual animal bones were then allocated evenly as substrates across the 9 knife types to ensure an even distribution of rib sizes and individual animals per knife.

5.4 Force measurements

The measurement of force in relation to stabbing has been carried out (Miller and Jones, 1996; Chadwick *et al.* 1999; Horsfall *et al.*, 1999; 2005), but not in relation to the effect force had on marks made by knives in bone. Knives and weapons used to make marks on previous forensic studies had no measured force, and force was measured as a variable to establish whether mark features made by knives in bone had any relationship with force by measuring force in relation to each knife cut made.

Forces were measured using a floor-mounted, 600x400 mm Kistler Force plate (Figure 5.5). The force plate was capable of measuring forces down to 10 mN, and covers a measuring range of up to 20 kN. It is capable of calculating medio-lateral forces (F_x), anterior-posterior forces (F_y) and vertical forces (F_z), as shown in Table 5.2.

Parameter	Calculation	Description
Fx	= fx12 + fx34	Medio-lateral force 1)
Fy	= fy14 + fy23	Anterior-posterior force 1)
Fz	= fz1 + fz2 + fz3 + fz4	Vertical force

Table 5. Error! Main Document Only.**: Table showing how the force plate calculates forces using sensor locations shown in Figure 5.5 (Kistler, 1998)**

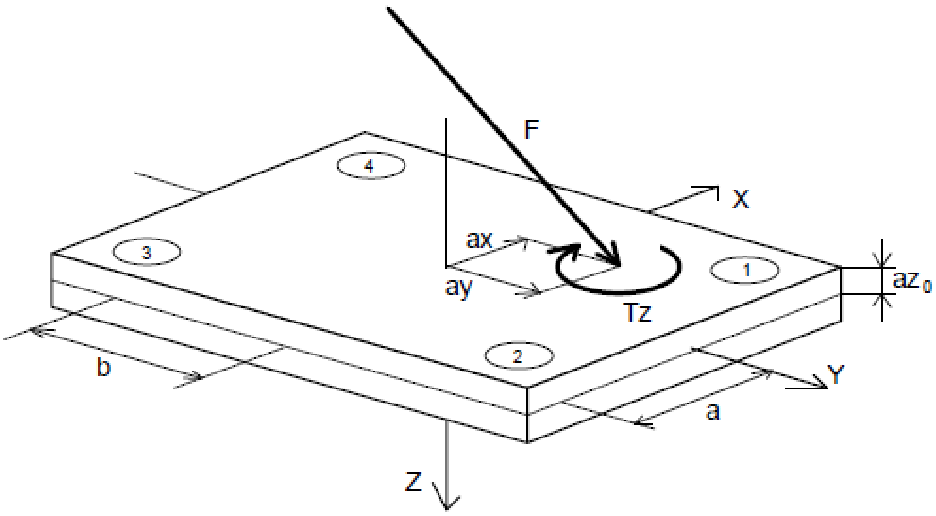

Figure 5.5: Diagram of Kistler force plate showing points used to calculate force using a range of points on the plate (taken from Kistler, 1998). See Table 5.2 for calculations using these points.

As the force plate was floor mounted, a platform was devised to sit on top of the force plate, and the force plate was calibrated to account for the platform. In order to make the marks, the ribs were placed, in turn, into a vice. The vice grips were placed on the vertebral body only, in order to prevent the creation of marks by the grips on the rib itself (Figure 5.6 and Figure 5.7).

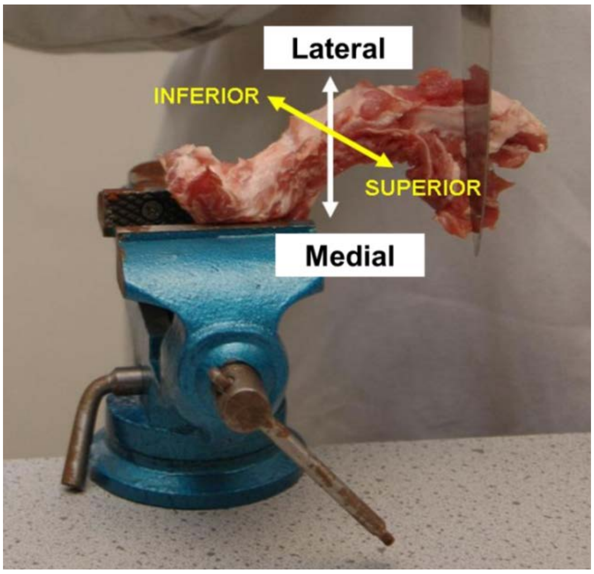

Figure 5.6: Photograph of rib held in vice, also showing relative anatomical terminology.

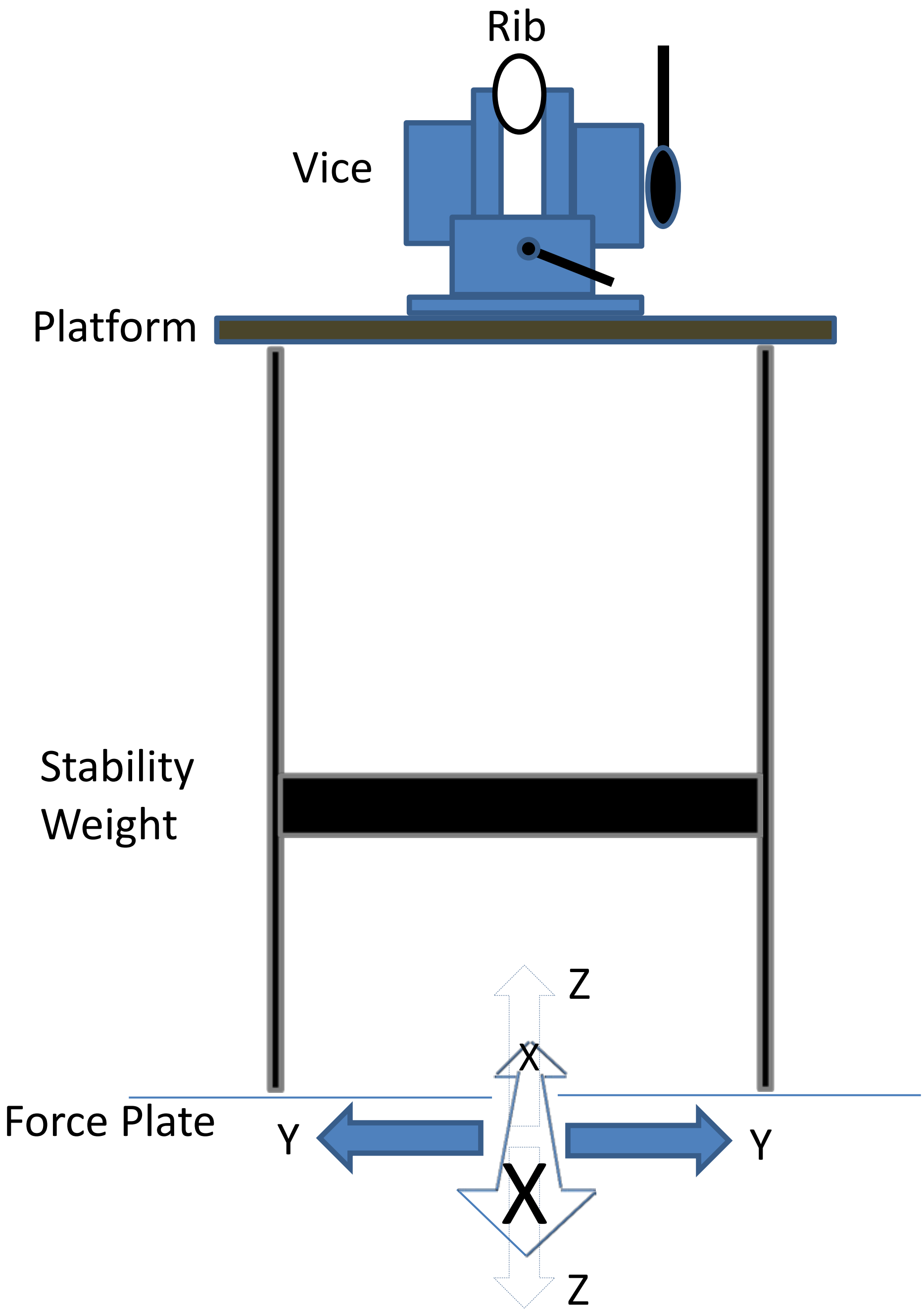

Figure 5.7: Schematic diagram of platform sat on force plate, and associated force directions. The superior/inferior planes of the rib (Figure 5.6) are parallel in relation to the anterior/posterior force planes (Fy).

5.5 Making the marks

Mechanical application and manual application of knife blades to a substrate are discussed in Chapter 4. A range of volunteer participants were approached to assist in making marks manually on bone.

All marks were made on bone and tissue declared fit for human consumption. The exact PMI for the specimens was unknown; however, marks were made within 48 hours of obtaining the specimens. Previous studies had shown that the method used in stabbing could have an impact on the force applied (Miller and Jones, 1996 and Horsfall *et al.*, 2005) and therefore participants observed a demonstration, and were instructed to use an overhand stabbing motion (Figure 5.8) from a fixed height (Figure 5.9), to control for any individual interpretation of how the knife should be applied to the bone. A wide frame with a clear, inelastic plastic membrane was placed over the force plate/platform/vice apparatus, and participants were instructed to start each stab with the butt of the knife blade touching the plastic. The frame was 1.3 m high, and the platform and vice was 0.73 m high, giving a distance of approximately 0.57 m between the membrane and the top of the vice/rib. This did not take into account the length of the knives, which further narrows the gap.

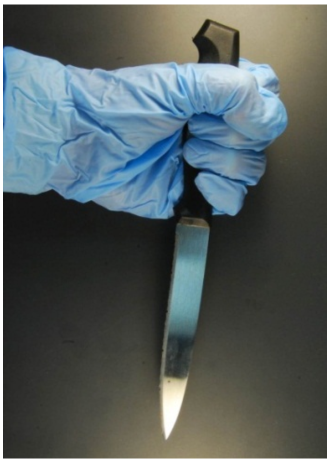

Figure 5.8: Photograph showing overhand-stab hand-grip

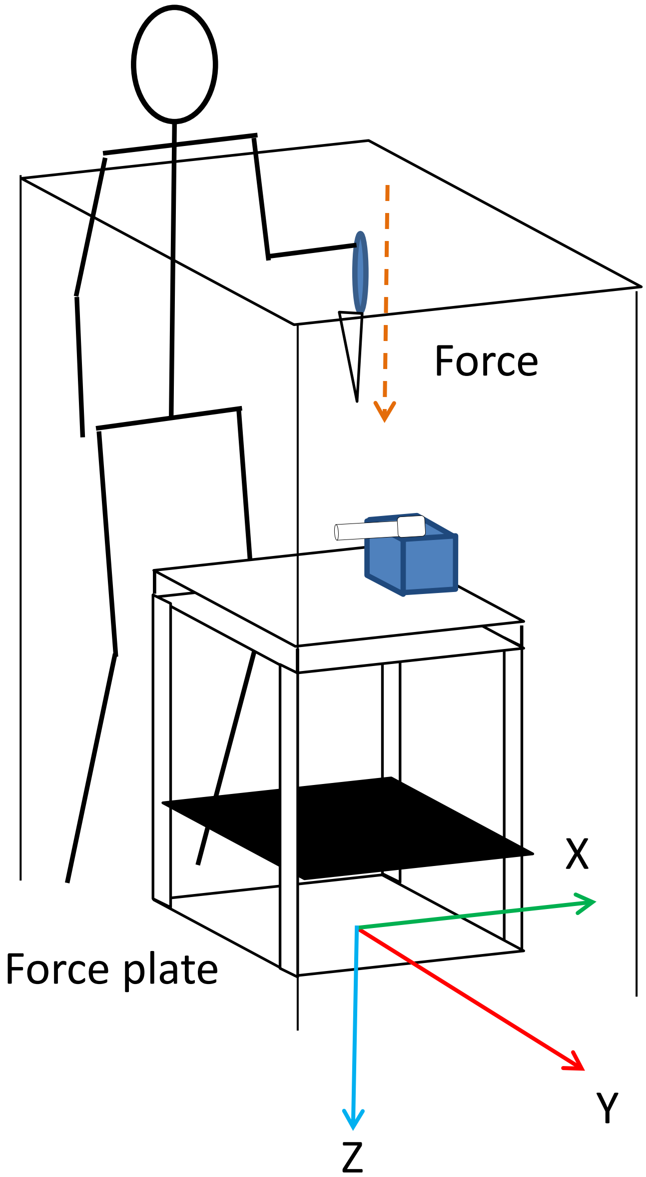

Figure 5.9: Schematic diagram of force plate, platform and external height frame. Participant action required 10 overhand stabs starting from top of external frame.

Participants were given 90 seconds, and asked to make 10 marks aiming for the superior surface of the rib, using the frame as a guide for height, moving from left to right, and using an overhand stroke with the same force each time. For the 90 second period, the force plate was activated; in addition, participants were monitored, and the total number of stab attempts noted. Each participant was allocated one knife from the sample set, and asked to produce 10 marks moving from left to right. Both the knife and the rib used were predetermined for reasons discussed later.

5.6 Controls and participants

Before participant marks were made, the author carried out the experiment described above for each knife, so the entire knife sample set had marks made by the same operator.

The study participant group recruited volunteers (n=23) to make marks on bones for examination.

5.7 Maceration (tissue-removal) technique

In order for marks on bone to be observed using microscopy, the adhering tissue needed to be carefully removed from the surface by maceration. Before maceration, each bone was examined and the number of visible flesh wounds recorded, in order to give a comparison between forces recorded, marks made in flesh, and the marks found in the bone post-maceration.

Each bone was labelled and suspended in a glass container containing a solution with 1 litre of distilled water to 1 “Daz” enzyme detergent tablet. The ribs were simmered at a temperature of 65-70 degrees centrigrade until the flesh was soft and easy to remove (approximately four hours). Suspending the bones prevented the cut-marked surfaces contacting either the sides of the container or other bone surfaces, which could potentially cause damage to the cuts or the bone surface (White, 1992). The bones were removed from the solution, gently rinsed in distilled water and the attached flesh was carefully removed using plastic forceps, avoiding contact with the bone surface until all remaining traces of flesh and periosteum were removed from the bones. The ribs were weighed post-maceration, and the number and position of marks visible on the bone recorded.

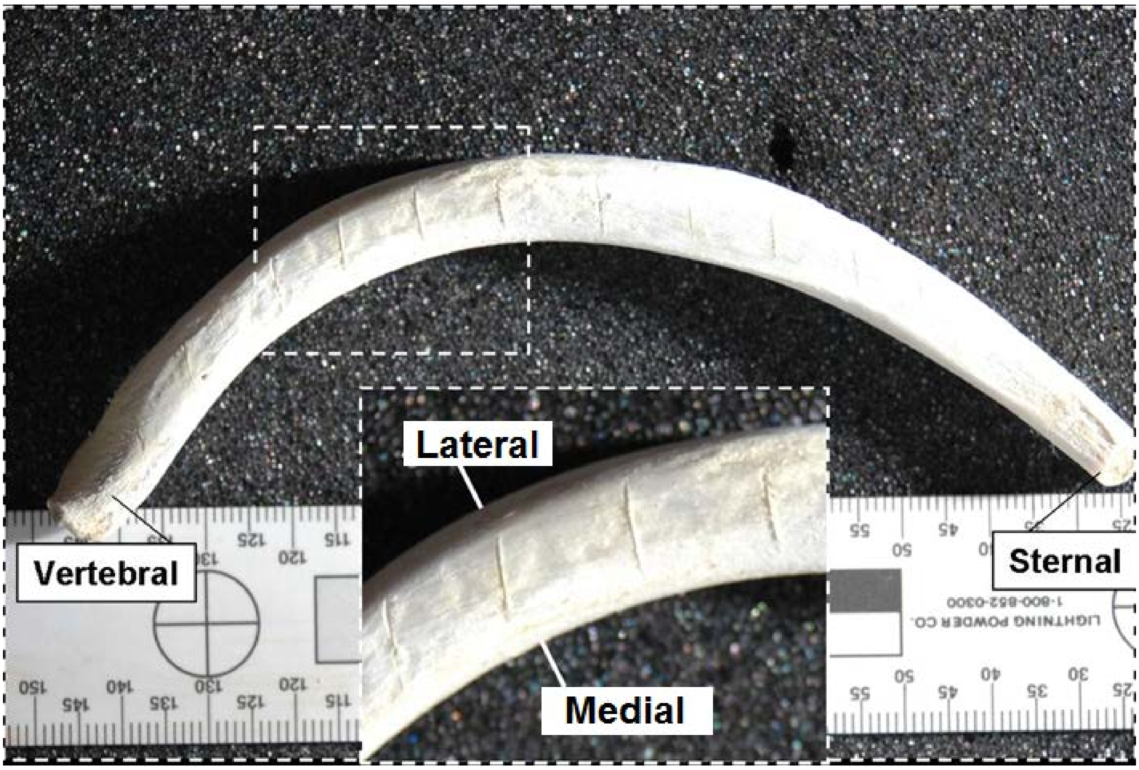

Figure 5.10: Image indicating directional terms for defleshed rib containing serrated incisions. Superior is facing the camera.

5.8 Microscopy

Marks were examined using a Leica S60E Transmitted Light Stereomicroscope with a magnification range of x6.3 and x40. The bones were placed on free-standing, moveable supports to prevent marks from lying on a hard surface. This also permitted manipulation under the microscope in order to view different aspects of the cuts, because changing the orientation of a specimen can reveal previously unobserved features (Shipman and Rose, 1983).

Lengths and widths were not recorded because accurate measurements are made at magnifications of 50x or more, and callipers do not give accurate measurements for indented features like cut marks (Shipman and Rose, 1983). The incident light source for low power microscopy was also systematically altered (Blumenschine *et al*., 1996) in order to ensure accurate observations of any particular feature.

5.9 Mark Classification

During mark analysis, it was considered that the action of the blade might provide a range of information at different points in the mark as a result of incision and subsequent removal of the weapon. For this reason, it was proposed that the kerf should be deliberately assessed in three sections: the main channel, and the two mark tips (Figure 5.11).

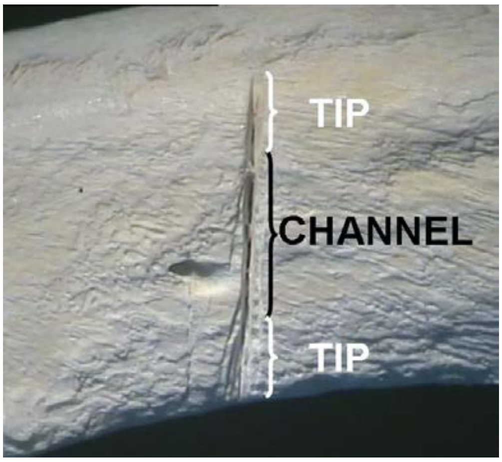

Figure 5.11: A fine-edged blade, imaged on a Projectina Comparison Macroscope at x105. The kerf sections are labelled.

The mark tips were the defined extremities of the kerf, and named according to their proximity to the nearest anatomical border, e.g., the anterior tip was the end of the kerf approaching the anterior border of the bone. Note the very different shapes of the tips in Figure 5.11; the anterior tip narrowly tapers, in contrast to the flared and rounded posterior tip. The main channel was the body of the kerf, located between the medial and lateral tips. Determination of the tips for classification was either:

- From the tip apex to the point at which the tip reaches a maximum or minimum constant width, or

- 10% of the maximum kerf length, from the apex of the tip,

whichever was the greater could then be applied. The first method was more appropriate for tapered tips. The abrupt endings of square or rounded tips made the second method more appropriate. The channel was then classified as the area between the two designated tips (Figure 5.11 and Figure 5.12).

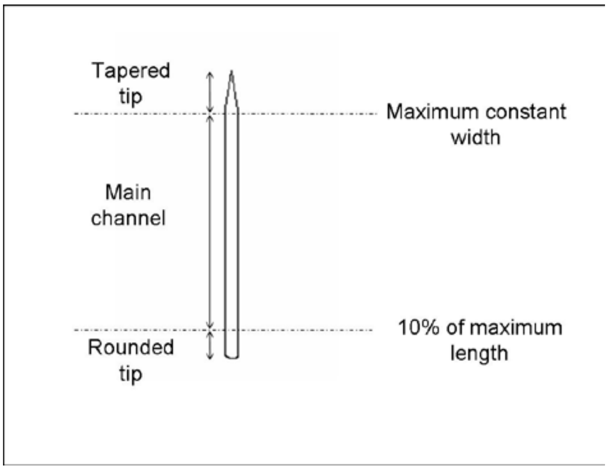

Figure 5.12: Schematic kerf diagram, illustrating two separate methods of tip length determination.

There was no published detailed morphological classification system specific to metal blade incision marks on bone in a forensic context. It was therefore necessary to create a classification system based on terms compiled from published works in archaeology, and a few limited terms from the forensic papers that have examined a knife blade against other types of trauma (a review is given in Chapter 2 and 3). The classification scheme created for this experiment can be seen in Table 3.3.

In addition to examining the kerf characteristics, the immediate area of bone surrounding the each part of the mark was also examined and noted on the same table. The kerf features examined are summarised under the headings below. Cited references detail where the features have been previously discussed or used experimentally. Where no citations are marked, no significant reference to that feature is noted in the literature. The classification form used to assess each mark can be seen in the Appendix.

5.10 Bone surface features

Bromage and Boyde (1984) acknowledged that aspects of the individual bone could contribute to the morphology of a cut mark, and Eickhoff and Herrman (1985) acknowledged the surface made a difference to mark depth; therefore the bone surface features were recorded.

5.10.1 Porosity

The presence of surface pores in the surrounding bone was noted. The presence of multiple pores in numerous areas surrounding the mark is classified as a porous surface (Tennick *et al.,* 2008).

5.10.2 Gradient

The bone gradient was the degree of surface slope of the area surrounding the cut. A level surface was categorised with no gradient, a surface with a slope apparently greater than 45^{o} was classified as a steep gradient, and a surface with an angle less than 45^{o} was a shallow gradient (Tennick *et al.,* 2008).

5.10.3 Texture

The surface of bone was scored according to its appearance. Cortical bone that showed little variation in surface topography was classed as smooth, whereas a visibly undulating surface appearance was classified as textured. In areas of mixed topography, classification focussed around the immediate area of the incision for scoring purposes (Tennick *et al.,* 2008).

5.11 Kerf features

Kerf features are defined below. Where a characteristic has been referred to in previous studies, citations are included, and more details can be found in Chapters 2 and 3. In some instances new vocabulary has been applied. Tip shape and bifurcation apply only to the tips of the kerf.

5.11.1 Tip shape

The shape of each tip of the kerf was recorded. Four tip categories were used:

Rounded - The tip margins had a rounded appearance (Tennick *et al.,* 2008).

Tapered – The tip margins had a tapered appearance at one or both margins (Tennick *et al.,* 2008).

Square – The tip margins had a squared appearance (Alunni-Perret *et al.* (2006).

Other – Any other shape formed by the tip margins (Tennick *et al.,* 2008).

5.11.2 Bifurcation

Bifurcation of the tip is when the kerf splits into more than one channel. Eickhoff and Hermann (1985) documented this affect as “splitting” on experiments with stone tools. Bifurcation was recorded as present or absent.

5.12 Profile and wall characteristics

5.12.1 Cross-section profile

Cross-section profile was a description of the profile shape of the kerf. Shape was recorded as V, U, I_I or other. (Potts and Shipman, 1981, Shipman, 1983, Greenfield, 1999, and Blumenschine *et al*., 1996)

5.12.2 Wall gradient

Wall gradient was the slope of the kerf wall in relation to the floor of the kerf. The following broad criteria were used to classify the wall gradient:

- **Very Steep**: 90 degree wall angle to kerf floor
- **Steep**: Angle of wall between 45-90 degrees to kerf floor
- **Shallow**: Angle of wall to kerf floor was less than 45 degrees
- **Very Shallow**: Wall present but angle of wall to floor was close to zero
- **None**: No wall was present

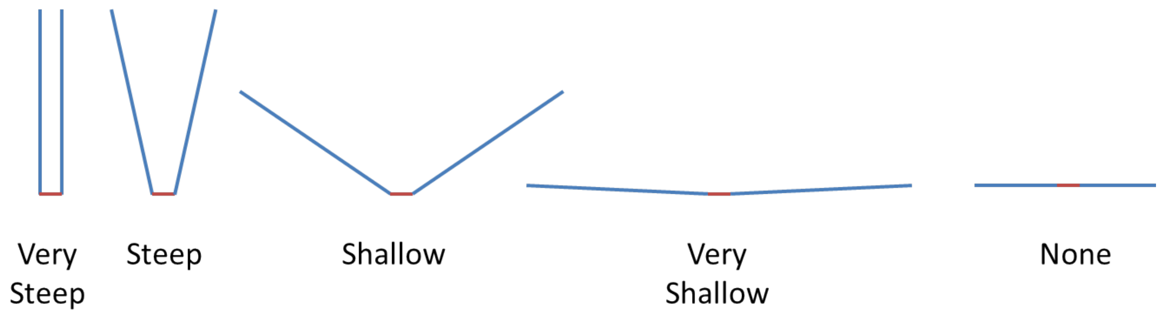

Figure 5.13: Diagram series illustrating wall gradients. The floor is shown in red, and the walls in blue. Both walls have the same classification for the example, but are classified separately. Kerf walls can vary in their classification within the same mark.

Each wall was scored individually. Walls were referred to with appropriate anatomical prefixes according to their nearest relative anatomical location on the rib e.g. vertebral walls and medial walls.

5.12.3 Wall projections

Wall projections were bony protrusions (Tennick *et al.,* 2008), distinguished from other bony debris because the projections were attached to the kerf wall. The number of wall projections, and their size, were categorised for each wall of the kerf. A classification of many projections was applied if there were more than 5 projections visible on the wall. Few projections were recorded if there were 5 or fewer projections on the wall. The size of projections was broadly classified as large or small. Large projections were greater than 25% of the width of the kerf, and small projections were less than 25% of the kerf width. They were distinguished from wall projections as they appeared physically joined to the walls of the kerf.

5.13 Margin Characteristics

5.13.1 Margin regularity

Margins were referred to in a number of papers (Shipman, 1983, Wenham, 1989 and Loe and Cox, 2005), and Alunni-Perret *et al.* (2005) used the term edges to describe the margins, as well as descriptive terms such as irregular and even, although these were not clearly defined. Regularity referred to the linear nature of the margins of the kerf; continuous deviation from a linear form was categorised as an irregular margin. Regular margins were so classified because they did not deviate from a linear form. Each margin was marked separately (vertebral/sternal).

5.13.2 Margin definition

Kerf margin definition was scored according to the sharpness, clarity and precision of the edge. Defined edges were precise and clearly formed. Undefined edges lacked precision and clarity .Each margin was marked separately (vertebral/sternal).

5.13.3 Margin splitting

The margins of the kerf were observed for signs of splitting. Margin splitting were scored as present or absent, and the location of the split was also documented (vertebral/sternal). An equivalent definition by Lewis (2008) was given as cracking, with reference to kerfs made by swords.

5.13.4 Lateral Ridging

This was a characteristic ‘peaking’ at either or both margins, with a ridge forming along the margin’s edge . Alunni-Perret *et al.* (2005) documented a similar phenomenon known as “unilateral raising”, as it was observed at only one margin. In the experimental sample, when the presence of lateral ridging was noted, its location at either or both margins was also observed, and labelled according to the margin’s relative anatomical position (vertebral or sternal). It was marked as present or absent for each margin.

5.14 Floor Characteristics

This was defined as the nadir of the kerf; the area connecting the kerf walls. Observation of floor characteristics was be problematic, depending on both cross-section shape and the width of the mark, which was sometimes be too narrow for observations to be made. The presence of wall projections and debris in the kerf can also prevent a full examination of the floor by obscuring it from view. Alunni-Perret *et al*. (2005) described floors as even or irregular; three observations were proposed for the floors in this study. The characteristics scored for the kerf floor included definition, splitting, and arbitrary width.

5.14.1 Floor definition

Definition scored the precision and clarity of the floor shape, and in particular the relationship of the morphology at which the floor and the walls join. Clear boundaries between the floor and walls were scored as defined. Any ambiguity in this relationship was scored as an undefined floor.

5.14.2 Floor width

The width of the floor was arbitrarily scored as wide or narrow. Wide floors were those that were greater than 25% of the height of the mark. Narrow floors were less than 25% of the height of the mark.

5.14.3 Floor splitting

The presence of observable cracks in the kerf floor was known as floor splitting. This was observed as present or absent (Tennick *et al.,* 2008).

5.15 Debris Characteristics

Debris within the mark varied in size, shape and composition. The presence of debris inhibited the observation of some marks, but in each case was catalogued according to the following criteria:

5.15.1 Crushing

Many authors have described crushing in association with marks on bone (Potts and Shipman, 1981, Shipman, 1983, Blumenschine *et al.*, 1996, and Humphrey and Hutchison, 2001). Crushing is debris in the kerf that has a granular or crushed appearance. Marked as present or absent.

5.15.2 Flaking

Flaking has also been referred to in reference to marks including hacking trauma (Alunni-Perret *et al*. 2005) and sword marks (Wenham, 1989). Flaking is debris in the kerf that has a flat, flaked appearance. Marked as present or absent.

5.15.3 Size of debris fragment

Large fragments were greater than 25% of the width of the kerf, and small fragments are less than 25% of the kerf width. They were distinguished from wall projections as they appeared not to be physically joined to the kerf walls (Tennick *et al.,* 2008).

5.15.4 Type of debris

Kerf debris was categorised into three observable types; bone, tissue and metal. The presence of any debris type present was recorded (Tennick *et al.,* 2008).

5.16 Summary

The list above is a comprehensive list of potential classification features for a cut mark, drawn from a range of wide range of archaeological sources, and a limited number of sources in forensic science. These criteria have been used to assess cut marks produced in fleshed ribs by a range of operators. The force used to make the marks has been measured. The next chapter documents the results of the experiment.

Chapter 6 Results

6.1 Introduction

All data were transcribed to numeric values, to allow statistical analysis using the SPSS 19.0 package. For coding details, please see Appendix 1. The raw data can be viewed in the “RAWDATA” file on the accompanying disk.

The Chi-squared test (χ^2) for association was used for analysis, in conjunction with the Fisher’s exact test, which is more accurate when sample numbers are small.

Cut mark characteristics (n=23) were tested in three different areas of the kerf; the medial tips, lateral tips, and main channel. These were tested against the knife blade classes (n=3), knife blade subclasses (n=9), and the overall tip shape (n=2) described in Chapter 5 to establish whether cut mark features can be attributed to blade characteristics. The knife blade types, groups and tip shape were all tested against each individual mark characteristic, and a contingency table was produced.

The Chi-squared test and Fisher’s exact test was used to examine the relationships between observed kerf features and blade characteristics. In each case, the null hypothesis assumes that the variables are independent of each other and that there is no association between the two variables tested. The null hypothesis can be rejected if the p-value, or probability, is smaller than 0.05. In the results tables in the following section, results of significant association are emboldened.

The classification of kerf features was not always possible, as a result of debris filling or obscuring the channel, or the degree of angle, depth or width of the cut preventing full analysis of the kerf. Any ambiguous or unclear features were categorised as “Unobservable”. Unobservable classifications are not deemed diagnostic and therefore cases with unobservable features have been removed from the samples tested.

6.2 Class blade features and kerf characteristics

6.2.1 Tip shape

The control group kerfs showed no significant association (p>0.05) between tip shape and knife class for either the medial or the lateral tips (Table 6.31).

The participant group kerfs also showed no significant association (p>0.05) with tip shape for the medial or lateral tips of the kerf (Table 6.31)

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	Medial tip	10.328	6	0.112	0.48	78
Control	Lateral tip	4.179	6	0.653	0.655	80
Participants	Medial tip	3.032	6	0.805	0.806	171
Participants	Lateral tip	7.068	6	0.315	0.306	169

Table 6.1: Results of χ2 test for association between tip shape and knife blade class for the control group and the participant group.

6.2.2 Bifurcation

Bifurcation in the control group kerfs showed no significant association ($p>0.05$) with knife class for the medial tip or the lateral tip (Table 6.2).

In contrast, the participant group kerfs demonstrated a significant association ($p<0.05$) with both the medial tips and lateral tips (Table 6.2).

Group	Kerf location	χ^2	df	p value	Fisher's exact test	N
Control	Medial tip	2.333	2	0.311	0.290	78
Control	Lateral tip	4.899	2	0.086	0.071	79
Participants	Medial tip	9.426	2	**0.009**	**0.014**	170
Participants	Lateral tip	10.468	2	**0.005**	**0.008**	172

Table 6.2: Results of χ^2 test for association between bifurcation and knife blade class for the control group and the participant group.

6.2.3 Cross section shape

The kerf cross section showed a significant association ($p<0.05$) at the main channel in the control group (Table 6.3)

For the participant kerfs, no significant association ($p>0.05$) exists between the knife class and the kerf cross-section shape (Table 6.3)

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	Medial tip	6.043	6	0.418	0.423	56
Control	Lateral tip	8.835	8	0.356	0.275	64
Control	Main channel	16.940	6	**0.010**	**0.006**	72
Participants	Medial tip	14.631	8	0.067	0.074	128
Participants	Lateral tip	8.468	6	0.206	0.229	121
Participants	Main channel	2.734	6	0.841	0.841	117

Table 6.3: Results of $\chi 2$ test for association between kerf cross-section shape and knife blade type for the control group and the participant group.

6.2.4 Wall gradient

The wall gradient for the control group showed that knife type and vertebral wall gradient demonstrated a significant association ($p<0.05$) between knife class and the Lateral Tip (LT), shown in Table 6.4. The sternal kerf wall has a significant association ($p<0.05$) with knife class for the main channel and the Medial Tip (MT) in the control group (Table 6.4).

The participant group demonstrated a significant association ($p<0.05$) between the sternal wall and the medial tip and the vertebral wall and the main channel. (Table 6.4).

Group	Kerf location	Wall location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	Vertebral	7.863	8	0.447	0.498	69
Control	MT	Sternal	13.943	6	**0.030**	**0.018**	69
Control	LT	Vertebral	18.025	8	**0.021**	**0.007**	71
Control	LT	Sternal	8.226	8	0.412	0.406	70
Control	MC	Vertebral	16.554	10	0.085	0.056	69
Control	MC	Sternal	12.875	6	**0.045**	**0.030**	79
Participants	MT	Vertebral	16.925	8	0.031	0.025	161
Participants	MT	Sternal	18.653	8	**0.017**	**0.015**	161
Participants	LT	Vertebral	12.083	6	0.060	0.049	155
Participants	LT	Sternal	12.299	8	0.138	0.115	154
Participants	MC	Vertebral	19.254	6	**0.004**	**0.004**	171
Participants	MC	Sternal	14.421	8	0.071	0.030	171

Table 6.4: Results of $\chi 2$ test for association between knife type and kerf wall (vertebral and sternal) for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.2.5 Wall projection frequency

For the control group, the frequency of wall projections at the tips shows a significant association ($p<0.05$) with knife class for the vertebral wall at the lateral tip (LT) and at the sternal wall for the main channel (MC). For the participant group, the vertebral and sternal walls in the main channel and the lateral tip exhibited a significant association ($p<0.05$) between wall projection frequency and knife class (Table 6.5).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	4.991	4	0.288	0.301	66
Control	MT	Sternal	2.572	4	0.632	0.635	66
Control	LT	Vertebral	11.791	4	**0.019**	**0.007**	71
Control	LT	Sternal	7.648	4	0.105	0.050	72
Control	MC	Vertebral	11.191	6	0.083	0.050	79
Control	MC	Sternal	9.519	4	**0.049**	**0.041**	79
Participants	MT	Vertebral	4.472	4	0.346	0.350	150
Participants	MT	Sternal	7.800	4	0.099	0.093	151
Participants	LT	Vertebral	4.818	4	0.307	0.337	154
Participants	LT	Sternal	16.998	4	**0.002**	**0.002**	154
Participants	MC	Vertebral	11.090	4	**0.026**	**0.015**	164
Participants	MC	Sternal	26.328	4	**0.001**	**0.001**	164

Table 6.5: Results of χ2 test for association between knife type and vertebral/sternal wall projection frequencies in control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.2.6 Wall projection size

The control group showed a significant association ($p<0.05$) between knife class and the size of wall projections for the main channel at the sternal wall, and the lateral tip at the vertebral wall; the medial tips demonstrated no significant association (Table 6.6).

In the participant group, vertebral wall projection size has no significant association ($p>0.05$) with knife class for any part of the kerf. Sternal wall projection size has a significant association ($p<0.05$) with knife type at the main channel and lateral tip (Table 6.6).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	5.138	4	0.273	0.207	64
Control	MT	Sternal	2.359	4	0.670	0.691	64
Control	LT	Vertebral	12.990	4	**0.011**	**0.008**	70
Control	LT	Sternal	9.527	6	0.146	0.078	72
Control	MC	Vertebral	12.085	6	0.060	0.051	79
Control	MC	Sternal	13.333	6	**0.038**	**0.034**	79
Participants	MT	Vertebral	5.693	6	0.427	0.428	151
Participants	MT	Sternal	10.222	6	0.141	0.114	151
Participants	LT	Vertebral	7.551	6	0.273	0.331	154
Participants	LT	Sternal	25.416	6	**0.001**	**0.001**	154
Participants	MC	Vertebral	5.385	6	0.495	0.514	164
Participants	MC	Sternal	19.953	6	**0.003**	**0.004**	164

Table 6.6: Results of χ2 test for association between knife type and vertebral/sternal wall projection size for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.2.7 Margin regularity

The control group has a significant association ($p<0.05$) between margin regularity and knife class at the main channel vertebral margin, and the medial tip sternal margin (Table 6.7).

The participant group has a significant ($p<0.05$) association between margin regularity and knife class for the vertebral and sternal margins at the medial tips, and the lateral tip sternal margins (Table 6.7).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	2.353	2	0.308	0.303	77
Control	MT	Sternal	8.833	2	**0.012**	**0.009**	78
Control	LT	Vertebral	7.295	4	0.121	0.670	72
Control	LT	Sternal	7.417	4	0.115	0.104	78
Control	MC	Vertebral	18.716	4	**0.001**	**0.001**	79
Control	MC	Sternal	5.976	4	0.201	0.111	78
Participants	MT	Vertebral	6.191	2	**0.045**	**0.048**	170
Participants	MT	Sternal	6.791	2	**0.034**	**0.029**	169
Participants	LT	Vertebral	0.935	2	0.627	0.664	171
Participants	LT	Sternal	10.051	2	**0.007**	**0.006**	168
Participants	MC	Vertebral	0.640	2	0.726	0.739	173
Participants	MC	Sternal	1.467	2	0.480	0.491	171

Table 6.7: Results of χ2 test for association between knife type and margin regularity for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.2.8 Margin definition

For the control group, a significant association ($p<0.05$) exists between knife class and margin definition for the vertebral margins at the main channel, but no significant association exists between these variables at the tips (Table 6.8).

The participant group demonstrates a significant association ($p<0.05$) between knife class and margin definition for the sternal margin at the medial tip and the main channel (Table 6.8).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	1.377	2	0.502	0.498	78
Control	MT	Sternal	5.541	2	0.063	0.075	78
Control	LT	Vertebral	5.306	2	0.070	0.075	79
Control	LT	Sternal	3.716	2	0.156	0.170	79
Control	MC	Vertebral	6.779	2	**0.034**	**0.029**	79
Control	MC	Sternal	2.971	2	0.226	0.307	79
Participants	MT	Vertebral	3.250	2	0.197	0.221	171
Participants	MT	Sternal	7.088	2	**0.029**	**0.029**	170
Participants	LT	Vertebral	2.377	2	0.305	0.310	170
Participants	LT	Sternal	3.583	2	0.167	0.166	168
Participants	MC	Vertebral	3.917	2	0.141	0.154	170
Participants	MC	Sternal	20.748	2	**0.001**	**0.001**	171

Table 6.8: Results of χ2 test for association between knife type and margin definition for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.2.9 Margin splitting

No significant association ($p>0.05$) was recorded between knife class and margin splitting for any part of the kerf in either group (Table 6.9).

Group	Kerf location	Wall location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	Vertebral	0.841	2	0.657	1.000	76
Control	MT	Sternal	N/A	N/A	N/A	N/A	N/A
Control	LT	Vertebral	0.027	2	0.987	1.000	79
Control	LT	Sternal	0.854	2	0.653	0.677	78
Control	MC	Vertebral	N/A	N/A	N/A	N/A	N/A
Control	MC	Sternal	N/A	N/A	N/A	N/A	N/A
Participants	MT	Vertebral	2.361	2	0.307	0.202	173
Participants	MT	Sternal	4.422	2	0.110	0.195	172
Participants	LT	Vertebral	0.601	2	0.740	0.694	168
Participants	LT	Sternal	2.194	2	0.334	0.310	167
Participants	MC	Vertebral	2.367	2	0.306	0.268	171
Participants	MC	Sternal	N/A	N/A	N/A	N/A	N/A

Table 6.9: Results of $\chi 2$ test for association between knife type and margin splitting for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/A - Not Applicable; in N/A cases no tests carried out as the result was constant.

6.2.10 Floor definition

A significant association ($p<0.05$) was recorded between knife class and floor definition for the main channel in the control group, and no significant associations ($p>0.05$) were found in the participant group for any part of the kerf (Table 6.10)

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	6.505	2	0.390	0.041	50
Control	LT	8.785	4	0.067	0.069	71
Control	MC	9.101	2	**0.011**	**0.009**	71
Participants	MT	7.299	4	0.121	0.073	124
Participants	LT	1.965	2	0.374	0.402	119
Participants	MC	0.717	2	0.699	0.721	121

Table 6.10: Results of $\chi 2$ test for association between knife type and for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.2.11 Floor width

The control group exhibited a significant association ($p<0.05$) between floor width and knife class for the main channel but not for the medial and lateral tips (Table 6.11).

The participant group had no significant association ($p>0.05$) between floor width and knife class at any part of the kerf (Table 6.11).

Group	Kerf location	χ^2	df	p value	Fisher's exact test	N
Control	MT	1.893	2	0.388	0.377	51
Control	LT	4.710	2	0.095	0.096	59
Control	MC	8.003	2	**0.018**	**0.016**	70
Participants	MT	0.456	2	0.796	0.810	123
Participants	LT	0.218	2	0.897	0.919	117
Participants	MC	3.177	2	0.204	0.224	114

Table 6.11: Results of χ^2 test for association between knife type and for floor width control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.2.12 Floor splitting

No significant association ($p>0.05$) was recorded between knife class and floor splitting for any part of the kerf in either group (Table 6.12).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	MT	1.201	2	0.549	0.527	52
Control	LT	N/A	N/A	N/A	N/A	N/A
Control	MC	2.698	2	0.260	0.239	70
Participants	MT	0.594	2	0.743	0.736	127
Participants	LT	4.825	4	0.306	0.340	118
Participants	MC	2.730	2	0.255	0.259	119

Table 6.12: Results of χ2 test for association between knife type and floor splitting for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/A - Not Applicable; in N/A cases no tests carried out as the result was constant.

6.2.13 Presence of debris

A significant association ($p<0.05$) exists for the control and the participant group between the knife type and the presence of debris at the medial tips (Table 6.13).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	MT	9.314	2	**0.009**	**0.010**	76
Control	LT	0.919	2	0.632	0.680	77
Control	MC	5.089	2	0.079	0.103	80
Participants	MT	8.630	2	**0.013**	**0.013**	168
Participants	LT	0.616	2	0.735	0.756	169
Participants	MC	2.493	2	0.288	0.300	170

Table 6.13: Results of χ2 test for association between knife type and the presence of debris for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.2.14 Debris fragment type

Neither the control nor the participant group shows a significant association ($p>0.05$) between debris fragment type and knife class (Table 6.14).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	MT	7.131	4	0.129	0.126	77
Control	LT	9.871	6	0.130	0.128	77
Control	MC	12.340	6	0.055	0.068	81
Participants	MT	12.149	6	0.059	0.037	168
Participants	LT	4.018	6	0.674	0.664	164
Participants	MC	13.562	8	0.094	0.055	168

Table 6.14: Results of χ2 test for association between knife type and the type of debris fragment for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.2.15 Debris fragment size

The control group has significant association ($p<0.05$) between the knife class and debris fragment size for the main channel and the medial tip of the kerf only (Table 6.15).

The participant group has no significant association between knife class and fragment size for the lateral tip, but does demonstrate a significant association ($p<0.05$) at the medial tip (Table 6.15)

Group	Kerf location	χ^2	df	p value	Fisher's exact test	N
Control	MT	14.488	6	**0.025**	**0.028**	77
Control	LT	10.314	6	0.112	0.042	77
Control	MC	28.227	6	**0.001**	**0.001**	81
Participants	MT	16.790	6	**0.010**	**0.006**	168
Participants	LT	5.647	6	0.464	0.452	164
Participants	MC	10.184	6	0.117	0.106	169

Table 6.15: Results of χ^2 test for association between knife type and the size of debris fragment for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.2.16 Debris material

The control group shows a significant association ($p<0.05$) between knife class and the type of debris material at the main channel and the medial tip (Table 6.16). The participant group shows a significant association ($p<0.05$) with the medial tip of the kerf (Table 6.16).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	17.751	6	**0.007**	**0.006**	77
Control	LT	8.344	8	0.401	0.474	76
Control	MC	16.933	6	**0.010**	**0.003**	78
Participants	MT	17.824	8	**0.023**	**0.010**	167
Participants	LT	9.685	6	0.139	0.122	165
Participants	MC	10.704	10	0.381	0.327	171

Table 6.16: Results of $\chi 2$ test for association between knife type and the type of debris material for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.2.17 Lateral ridging

The control group had significant associations ($p<0.05$) between knife class and lateral ridging for the vertebral margins and sternal margins at the lateral tip, and the vertebral margin at the medial tip (Table 6.17).

The participant group had significant associations ($p<0.05$) between knife type and lateral ridging for the sternal margins at the lateral tip and main channel. There are significant associations ($p<0.05$) at the medial tip and main channel vertebral margins (Table 6.17).

Group	Kerf location	Margin location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	9.540	2	**0.008**	**0.013**	79
Control	MT	Sternal	0.506	2	0.776	0.743	78
Control	LT	Vertebral	8.925	2	**0.012**	**0.010**	80
Control	LT	Sternal	6.637	2	**0.036**	**0.027**	80
Control	MC	Vertebral	3.524	2	0.172	0.206	79
Control	MC	Sternal	0.793	2	0.673	0.671	80
Participants	MT	Vertebral	12.693	2	**0.002**	**0.001**	177
Participants	MT	Sternal	2.593	2	0.273	0.274	176
Participants	LT	Vertebral	3.496	2	0.174	0.211	173
Participants	LT	Sternal	7.031	2	**0.030**	**0.027**	173
Participants	MC	Vertebral	13.495	2	**0.001**	**0.002**	176
Participants	MC	Sternal	11.373	2	**0.003**	**0.003**	176

Table 6.17: Results of χ2 test for association between knife type and the presence of lateral ridging at the sternal/vertebral margins, for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.2.1 Summary

The significant associations (p<0.05) identified between knife type and kerf features have been summarised in. There are 21 features that have significant associations with the knife type for the control group, and 20 features for the participant group. The greatest number of significant associations are around the main channel, followed by the medial tip, and finally the lateral tip has the fewest significant associations.

Experiment group	Control	Participants	Control	Participants	Control	Participants
Kerf location	*Medial tip*	*Medial tip*	*Lateral tip*	*Lateral tip*	*Main channel*	*Main channel*
Kerf features						
Tip shape						
Bifurcation		●		●		
X-Section					●	
V. Gradient			●			●
S. Gradient	●	●			●	
V. No.wall projections			●			●
S. No. wall projections				●	●	●
V. Projection size			●			
S. Projection Size				●	●	●
V. Margin Regularity		●			●	
S. Margin Regularity	●	●		●		
V. Margin Definition					●	
S. Margin Definition		●				●
V. Margin Splitting						
S. Margin Splitting						
Floor Definition					●	
Floor Splitting						
Floor Width					●	
Debris presence	●	●				
Debris fragment type						
Debris size	●	●			●	
Debris material	●	●			●	
V. Lateral Ridging	●		●			●
S. Lateral Ridging			●	●		●

Table 6.18: Summary table showing significant associations by group, kerf location and kerf feature. Blank cells have no significant association. Black circles mark significant associations.

6.3 Sub-class blade features and kerf characteristics

6.3.1 Tip shape

The control group kerfs showed no significant association (p>0.05) between tip shape and knife sub-class type for either the medial or the lateral tips (Table 6.19).

The participant group kerfs also showed no significant association (p>0.05) between knife sub-class type and tip shape for the medial or lateral tips of the kerf (Table 6.19).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	Medial tip	28.511	24	0.239	0.216	78
Control	Lateral tip	24.048	24	0.517	0.367	80
Participants	Medial tip	21.294	24	0.584	N/C	171
Participants	Lateral tip	21.206	24	0.627	N/C	169

Table 6.19: Results of χ2 test for association between tip shape and knife blade sub-class type for the control group and the participant group. NC = Not calculated.

6.3.2 Bifurcation

Bifurcation in the control group kerfs showed no significant association ($p>0.05$) with knife sub-class type to the medial tip or the lateral tip (Table 6.20).

In contrast, the participant group kerfs demonstrated a significant association ($p<0.05$) with both the medial tips and lateral tips (Table 6.20).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	Medial tip	13.609	8	0.093	0.06	79
Control	Lateral tip	7.796	8	0.454	0.454	79
Participants	Medial tip	24.214	8	**0.002**	**0.003**	169
Participants	Lateral tip	16.45	8	**0.036**	**0.050**	172

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Table 6.20: Results of χ2 test for association between bifurcation and knife blade sub-class type for the control group and the participant group.

6.3.3 Cross section shape

The kerf cross section showed no significant association ($p>0.05$) with any part of the kerf in the control groups (Table 6.21).

For the participant kerfs, a significant association ($p<0.05$) exists between the knife type and the kerf cross-section shape (Table 6.21).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	Medial tip	23.636	24	0.483	0.489	56
Control	Lateral tip	33.438	24	0.095	0.126	62
Control	Main channel	32.583	24	0.113	0.052	72
Participants	Medial tip	36.698	24	**0.047**	N/C	126
Participants	Lateral tip	37.494	24	**0.039**	N/C	121
Participants	Main channel	41.49	24	**0.015**	N/C	117

Table 6.21: Results of χ2 test for association between kerf cross-section shape and knife blade sub-class type for the control group and the participant group. NC = Not calculated..

6.3.4 Wall gradient

The wall gradient for the control group showed that knife type and vertebral wall gradient demonstrated a significant association ($p<0.05$) between knife type and the main channel (MC), and the Lateral Tip (LT), shown in Table 6.22. The sternal kerf wall has a significant association ($p<0.05$) with knife type for the main channel and the Medial Tip (MT) in the control group (Table 6.22).

The participant group demonstrated a significant association ($p<0.05$) between vertebral wall gradient in every part of the kerf (medial, lateral and main channel). Only the lateral tip showed a significant association with the sternal wall (Table 6.22).

Group	Kerf location	Wall location	χ^2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	33.122	32	0.412	0.252	69
Control	MT	Sternal	44.026	24	**0.008**	**0.001**	69
Control	LT	Vertebral	56.272	32	**0.005**	N/C	71
Control	LT	Sternal	37.206	32	0.242	0.105	70
Control	MC	Vertebral	48.1	32	**0.034**	**0.033**	79
Control	MC	Sternal	40.69	24	**0.018**	**0.032**	79
Participants	MT	Vertebral	56.713	32	**0.005**	N/C	161
Participants	MT	Sternal	40.424	32	0.146	N/C	161
Participants	LT	Vertebral	45.807	24	**0.005**	N/C	155
Participants	LT	Sternal	46.932	32	**0.043**	N/C	154
Participants	MC	Vertebral	63.123	24	**0.001**	N/C	171
Participants	MC	Sternal	42.904	34	0.094	N/C	170

Table 6.22: Results of χ^2 test for association between knife sub-class type and kerf wall (vertebral and sternal) for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated

6.3.5 Wall projection frequency

For the control group, the frequency of wall projections at the tips shows no significant association ($p>0.05$) with knife sub-class type for either wall of the kerf (Table 6.23). Both kerf walls in main channel had a significant association between frequency of wall projections and knife type (Table 6.23).

For the participant group, only the vertebral wall in the main channel exhibited any significant association ($p<0.05$) between wall projections and knife sub-class type (Table 6.23)

Group	Kerf location	Wall location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	Vertebral	18.964	16	0.271	0.324	66
Control	MT	Sternal	24.114	16	0.087	0.041	66
Control	LT	Vertebral	23.707	13	0.960	0.27	71
Control	LT	Sternal	18.153	16	0.315	0.213	72
Control	MC	Vertebral	32.094	16	**0.010**	**0.011**	79
Control	MC	Sternal	37.171	16	**0.002**	**0.002**	79
Participants	MT	Vertebral	10.911	16	0.815	0.79	150
Participants	MT	Sternal	16.194	16	0.439	N/C	151
Participants	LT	Vertebral	8.704	16	0.925	0.93	154
Participants	LT	Sternal	13.536	16	0.633	0.66	149
Participants	MC	Vertebral	28.230	16	**0.030**	N/C	164
Participants	MC	Sternal	13.871	16	0.608	N/C	150

Table 6.23: Results of $\chi 2$ test for association between knife sub-class type and vertebral/sternal wall projection frequencies in control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.6 Wall projection size

The control group showed a significant association ($p<0.05$) between knife sub-class type and the size of wall projections for the main channel only; the kerf tips demonstrated no significant association (Table 6.24).

In the participant group, vertebral wall projection size has no significant association ($p>0.05$) with knife type for any part of the kerf. Sternal wall projection size has a significant association ($p<0.05$) with knife sub-class type at the main channel and lateral tip, but not the medial tip (Table 6.24).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	21.848	24	0.588	0.394	66
Control	MT	Sternal	22.619	24	0.542	0.275	66
Control	LT	Vertebral	25.735	24	0.367	0.257	72
Control	LT	Sternal	25.899	24	0.358	0.363	72
Control	MC	Vertebral	40.937	24	**0.017**	**0.017**	79
Control	MC	Sternal	48.552	24	**0.002**	**0.003**	79
Participants	MT	Vertebral	12.644	16	0.699	0.68	147
Participants	MT	Sternal	12.375	16	0.718	N/C	145
Participants	LT	Vertebral	13.536	16	0.633	0.66	149
Participants	LT	Sternal	34.298	16	**0.005**	N/C	145
Participants	MC	Vertebral	13.871	16	0.608	N/C	150
Participants	MC	Sternal	34.247	16	**0.005**	N/C	142

Table 6.24: Results of χ2 test for association between knife sub-class type and vertebral/sternal wall projection size for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.7 Margin regularity

The control group has a significant association ($p<0.05$) between margin regularity for both margins and all parts of the kerf, with the exception of the medial tip vertebral margin, which demonstrates no significant association ($p>0.05$) (Table 6.25).

The participant group has no significant association ($p>0.05$) between margin regularity and knife sub-class type for either margin at any part of the kerf, with the exception of the sternal margin at the lateral tip (Table 6.25).

Group	Kerf location	Margin location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	11.879	8	0.157	0.147	77
Control	MT	Sternal	15.903	8	**0.044**	**0.030**	78
Control	LT	Vertebral	19.056	8	**0.015**	**0.005**	77
Control	LT	Sternal	26.49	16	**0.048**	**0.004**	77
Control	MC	Vertebral	25.263	8	**0.001**	**0.001**	78
Control	MC	Sternal	19.559	8	**0.012**	**0.012**	78
Participants	MT	Vertebral	13.122	8	0.108	0.141	170
Participants	MT	Sternal	13.426	8	0.980	0.880	169
Participants	LT	Vertebral	7.643	16	0.469	0.423	171
Participants	LT	Sternal	17.057	8	**0.030**	**0.020**	168
Participants	MC	Vertebral	9.778	8	0.281	0.281	173
Participants	MC	Sternal	14.123	8	0.079	0.079	171

Table 6.25: Results of χ2 test for association between knife sub-class type and margin regularity for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.8 Margin definition

For the control group, a significant association ($p<0.05$) exists between knife sub-class type and margin definition for both vertebral and sternal margins at the lateral tip and the main channel, but no significant association ($p>0.05$) exists between these variables at the medial tip (Table 6.26).

The participant group shows significant association ($p<0.05$) between knife sub-class type and margin definition for the sternal margin at the medial tip, and the vertebral margin in the main channel (Table 6.26).

Group	Kerf location	Margin location	$\chi2$	df	p value	Fisher's exact test	N
Control	MT	Vertebral	8.610	8	0.376	0.370	78
Control	MT	Sternal	11.678	8	0.166	0.138	79
Control	LT	Vertebral	15.661	8	**0.047**	**0.048**	79
Control	LT	Sternal	17.016	8	**0.030**	**0.026**	79
Control	MC	Vertebral	24.236	8	**0.002**	**0.001**	79
Control	MC	Sternal	16.251	8	**0.039**	**0.015**	79
Participants	MT	Vertebral	7.751	8	0.458	0.469	171
Participants	MT	Sternal	16.42	8	**0.037**	**0.035**	170
Participants	LT	Vertebral	7.734	8	0.460	0.407	170
Participants	LT	Sternal	10.634	8	0.223	0.246	168
Participants	MC	Vertebral	23.907	8	**0.002**	**0.001**	170
Participants	MC	Sternal	2.143	4	0.710	N/C	170

Table 6.26: Results of $\chi2$ test for association between knife sub-class type and margin definition for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.9 Margin splitting

No significant association ($p>0.05$) was recorded between knife sub-class type and margin splitting for any part of the kerf in either group (Table 6.27).

Group	Kerf location	Margin location	$\chi2$	df	p value	Fisher's exact test	N
Control	MT	Vertebral	7.161	8	0.519	0.522	76
Control	MT	Sternal	N/A	N/A	N/A	N/A	N/A
Control	LT	Vertebral	7.222	8	0.513	0.455	79
Control	LT	Sternal	5.832	8	0.666	0.679	78
Control	MC	Vertebral	N/A	N/A	N/A	N/A	N/A
Control	MC	Sternal	N/A	N/A	N/A	N/A	N/A
Participants	MT	Vertebral	7.313	8	0.503	0.400	173
Participants	MT	Sternal	10.346	8	0.242	0.125	172
Participants	LT	Vertebral	5.317	8	0.723	0.682	168
Participants	LT	Sternal	6.958	8	0.541	0.447	167
Participants	MC	Vertebral	8.550	8	0.382	0.380	171
Participants	MC	Sternal	N/A	N/A	N/A	N/A	N/A

Table 6.27: Results of $\chi2$ test for association between knife sub-class type and margin splitting for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/A - Not Applicable; in N/A cases no tests carried out as the result was constant.

6.3.10 Floor definition

No significant association ($p>0.05$) was recorded between knife sub-class type and floor definition for any part of the kerf in either group (Table 6.28)

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	MT	12.444	8	0.132	0.112	50
Control	LT	12.987	8	0.112	0.121	61
Control	MC	13.268	8	0.103	0.101	71
Participants	MT	12.949	8	0.114	0.104	123
Participants	LT	11.076	8	0.197	0.218	119
Participants	MC	7.693	8	0.464	0.457	121

Table 6.28: Results of χ2 test for association between knife sub-class type and for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.3.11 Floor width

The control group exhibited a significant association ($p<0.05$) between floor width and knife sub-class type for the main channel and the lateral tip, but not for the medial tip (Table 6.29).

The participant group had a significant association ($p<0.05$) between floor width and knife sub-class type for the main channel and medial tip, but not for the lateral tip (Table 6.29)

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	5.872	8	0.662	0.745	51
Control	LT	20.233	8	**0.009**	**0.006**	59
Control	MC	18.298	8	**0.019**	**0.020**	69
Participants	MT	18.377	8	**0.019**	**0.015**	123
Participants	LT	9.415	8	0.309	0.320	117
Participants	MC	19.23	8	**0.014**	**0.012**	114

Table 6.29: Results of $\chi 2$ test for association between knife sub-class type and for floor width control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.3.12 Floor splitting

No significant association (p>0.05) was recorded between knife sub-class type and floor splitting for any part of the kerf in either group (Table 6.30).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	N/A	N/A	N/A	N/A	N/A
Control	LT	N/A	N/A	N/A	N/A	N/A
Control	MC	12.256	8	0.140	0.157	70
Participants	MT	6.484	8	0.593	0.431	127
Participants	LT	6.859	8	0.552	0.521	117
Participants	MC	8.696	8	0.369	0.392	119

Table 6.30: Results of $\chi 2$ test for association between knife sub-class type and floor splitting for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/A - Not Applicable; in N/A cases no tests carried out as the result was constant.

6.3.13 Presence of debris

A significant association ($p<0.05$) exists for the control group between the knife sub-class type and the presence of debris at the medial tip and main channel, but not the lateral tip (Table 6.31).

The participant group demonstrates a significant association ($p<0.05$) for the medial tip only (Table 6.31).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	20.601	8	**0.008**	**0.004**	76
Control	LT	13.819	8	0.087	0.096	77
Control	MC	19.689	8	**0.012**	**0.006**	80
Participants	MT	46.79	32	**0.044**	N/C	169
Participants	LT	9.881	8	0.273	0.206	169
Participants	MC	7.691	8	0.464	0.523	170

Table 6.31: Results of $\chi 2$ test for association between knife sub-class type and the presence of debris for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.14 Debris fragment type

The control and the participant group kerfs both exhibit significant association ($p<0.05$) between the knife sub-class type and the type of debris fragments for the main channel; the tips, however, show no significant association ($p>0.05$) for either group (Table 6.32).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	20.455	16	0.2	0.157	77
Control	LT	32.093	24	0.125	0.05	77
Control	MC	71.439	24	**0.001**	N/C	81
Participants	MT	33.61	24	0.092	N/C	168
Participants	LT	32.311	24	0.119	N/C	164
Participants	MC	44.364	24	**0.007**	N/C	167

Table 6.32: Results of $\chi 2$ test for association between knife sub-class type and the type of debris fragment for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.15 Debris Fragment size

The control group has significant association (p<0.05) between the knife sub-class type and debris fragment size for the main channel and the lateral tip of the kerf only (Table 6.33).

Conversely, the participant group has no significant association(p>0.05) between knife type and fragment size for the main channel and lateral tip, but does demonstrate a significant association (p<0.05) at the medial tip (Table 6.33)

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	MT	35.86	24	0.057	0.050	77
Control	LT	41.863	24	**0.013**	**0.005**	77
Control	MC	71.439	24	**0.001**	N/C	81
Participants	MT	38.701	24	**0.029**	N/C	168
Participants	LT	32.624	24	0.112	N/C	164
Participants	MC	33.833	24	0.088	N/C	169

Table 6.33: Results of χ2 test for association between knife sub-class type and the size of debris fragment for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.16 Debris material

The control group shows a significant association ($p<0.05$) between knife sub-class type and the type of debris material at the main channel only, although the medial tip is very close to a result of association (Table 6.34). The participant group shows no significant association ($p>0.05$) for any part of the kerf (Table 6.34).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	45.799	24	0.050	0.040	77
Control	LT	35.369	32	0.301	0.270	76
Control	MC	50.225	24	**0.001**	N/C	78
Participants	MT	44.367	32	0.072	N/C	167
Participants	LT	22.282	24	0.562	N/C	165
Participants	MC	43.360	40	0.320	N/C	171

Table 6.34: Results of $\chi 2$ test for association between knife sub-class type and the type of debris material for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.17 Lateral ridging

The control group had significant associations ($p<0.05$) between knife sub-class type and lateral ridging for the vertebral margins at every part of the kerf. There are no significant associations at the sternal margins (Table 6.35).

The participant group had significant associations ($p<0.05$) between knife sub-class types and lateral ridging for both vertebral and sternal margins at the main channel, and the sternal margin at the lateral tip. There are no significant associations ($p>0.05$) at the medial tip (Table 6.35).

Group	Kerf location	Margin location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	28.557	8	**0.010**	**0.010**	79
Control	MT	Sternal	13.888	8	0.085	0.089	78
Control	LT	Vertebral	18.447	8	**0.018**	**0.021**	80
Control	LT	Sternal	10.864	8	0.210	0.149	80
Control	MC	Vertebral	19.267	8	**0.013**	**0.011**	80
Control	MC	Sternal	7.168	8	0.519	0.545	80
Participants	MT	Vertebral	13.689	8	0.090	0.062	177
Participants	MT	Sternal	6.706	8	0.569	0.559	176
Participants	LT	Vertebral	16.537	8	0.035	0.088	173
Participants	LT	Sternal	16.609	8	**0.034**	**0.029**	173
Participants	MC	Vertebral	25.256	8	**0.001**	**0.004**	176
Participants	MC	Sternal	27.544	8	**0.001**	N/C	176

Table 6.35: Results of χ2 test for association between knife sub-class type and the presence of lateral ridging at the sternal/vertebral margins, for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.3.18 Summary

The significant associations ($p<0.05$) identified between knife sub-class type and kerf features have been summarised in Table 6.36. There are 28 features that have significant associations with the knife type for the control group, and 23 features for the participant group. The greatest number of significant associations are around the main channel, followed by the lateral tip, and finally the medial tip has the fewest significant associations.

Experiment group	Control	Participants	Control	Participants	Control	Participants
Kerf location	*Medial tip*	*Medial tip*	*Lateral tip*	*Lateral tip*	*Main channel*	*Main channel*
Kerf features						
Tip shape						
Bifurcation		●		●		
X-Section		●		●		●
V. Gradient		●	●	●	●	●
S. Gradient	●			●	●	
V. No.wall projections					●	●
S. No. wall projections					●	
V. Projection size					●	
S. Projection Size				●	●	●
V. Margin Regularity			●		●	
S. Margin Regularity	●		●	●	●	
V. Margin Definition			●		●	●
S. Margin Definition		●	●		●	
V. Margin Splitting						
S. Margin Splitting						
Floor Definition						
Floor Splitting						
Floor Width		●	●		●	●
Debris presence	●	●			●	
Debris fragment type					●	●
Debris size		●	●		●	
Debris material					●	
V. Lateral Ridging	●		●		●	●
S. Lateral Ridging				●		●

Table 6.36: Summary table showing significant associations by group, kerf location and kerf feature. Blank cells have no significant association. Black circles mark significant associations.

6.4 Blade tip shape and kerf characteristics

The blades selected were all kitchen knives; SC3 was the only blade to have a rounded rather than a tapered tip. This knife is compared with the other knives to see if knife tip shape has an association with kerf features.

6.4.1 Tip shape

The control group kerfs showed no significant association ($p>0.05$) between kerf tip shape and blade tip shape for either the medial or the lateral tips (Table 6.37).

The participant group showed no significant association ($p>0.05$) between kerf tip shape and blade tip shape for either the medial or the lateral tips (Table 6.37).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	Medial tip	1.899	3	0.594	0.385	78
Control	Lateral tip	2.523	3	0.471	0.435	80
Participants	Medial tip	4.652	3	0.199	0.243	171
Participants	Lateral tip	1.301	3	0.729	0.856	169

Table 6.37: Results of $\chi 2$ test for association between kerf tip shape and knife tip shape for the control group and the participant group.

6.4.2 Bifurcation

Bifurcation in the control group kerfs showed no significant association ($p>0.05$) with knife tip shape for the control group or the participant group (Table 6.38)

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	Medial tip	0.256	1	0.613	1.000	79
Control	Lateral tip	0.023	1	0.880	1.000	79
Participants	Medial tip	0.052	1	0.820	0.646	170
Participants	Lateral tip	0.280	1	0.596	1.000	170

Table 6.38: Results of χ2 test for association between bifurcation and knife tip shape for the control group and the participant group.

6.4.3 Cross section shape

The kerf cross section showed no significant association ($p>0.05$) with knife tip shape at any part of the kerf in the control or the participant groups (Table 6.39).

Group	Kerf location	$\chi2$	df	p value	Fisher's exact test	N
Control	Medial tip	2.141	3	0.544	0.351	56
Control	Lateral tip	6.434	5	0.266	0.287	79
Control	Main channel	4.735	3	0.192	0.123	72
Participants	Medial tip	2.313	4	0.678	0.707	128
Participants	Lateral tip	5.867	3	0.118	0.111	121
Participants	Main channel	5.780	3	0.123	0.160	117

Table 6.39: Results of $\chi2$ test for association between kerf cross-section shape and knife tip shape for the control group and the participant group.

6.4.4 Wall gradient

The wall gradients of the kerf showed no significant association ($p>0.05$) with knife tip shape at any part of the kerf in the control group (Table 6.40).

The participant group showed a significant association ($p<0.05$) with knife tip shape at the lateral tip vertebral margin and the main channel sternal margin.

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	5.349	4	0.253	0.106	69
Control	MT	Sternal	6.024	3	0.110	0.182	69
Control	LT	Vertebral	1.421	4	0.840	0.572	71
Control	LT	Sternal	2.169	4	0.705	0.755	70
Control	MC	Vertebral	9.147	4	0.058	0.064	72
Control	MC	Sternal	1.697	3	0.638	0.859	79
Participants	MT	Vertebral	4.615	4	0.329	0.374	161
Participants	MT	Sternal	5.313	4	0.257	0.264	161
Participants	LT	Vertebral	8.251	3	**0.041**	**0.032**	154
Participants	LT	Sternal	6.395	4	0.172	0.171	154
Participants	MC	Vertebral	8.126	3	0.043	0.074	171
Participants	MC	Sternal	11.474	4	**0.022**	**0.013**	171

Table 6.40: Results of χ2 test for association between knife tip shape and the kerf wall (vertebral and sternal) for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.4.5 Wall projection frequency

Wall projection frequency displayed no significant association ($p>0.05$) with the knife tip shape for the control or the participant group (Table 6.41).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	0.578	2	0.749	1.000	66
Control	MT	Sternal	0.698	2	0.705	1.000	66
Control	LT	Vertebral	3.347	2	0.188	0.302	71
Control	LT	Sternal	0.561	2	0.756	1.000	72
Control	MC	Vertebral	0.301	3	0.960	1.000	79
Control	MC	Sternal	3.196	2	0.202	0.254	79
Participants	MT	Vertebral	1.424	2	0.491	0.858	150
Participants	MT	Sternal	3.852	2	0.146	0.187	151
Participants	LT	Vertebral	1.337	2	0.513	0.761	154
Participants	LT	Sternal	2.115	2	0.347	0.270	150
Participants	MC	Vertebral	1.128	2	0.569	0.657	164
Participants	MC	Sternal	2.157	2	0.340	0.354	164

Table 6.41: Results of χ2 test for association between knife tip shape and vertebral/sternal wall projection frequencies in control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.4.6 Wall projection size

Wall projection size shows no significant association ($p>0.05$) with knife tip shape for the control or the participant group (Table 6.42).

Group	Kerf location	Wall location	$\chi2$	df	p value	Fisher's exact test	N
Control	MT	Vertebral	0.331	2	0.847	1.000	64
Control	MT	Sternal	0.559	2	0.756	1.000	64
Control	LT	Vertebral	1.436	2	0.488	0.821	70
Control	LT	Sternal	0.099	3	0.992	1.000	72
Control	MC	Vertebral	0.516	3	0.915	0.944	79
Control	MC	Sternal	4.800	3	0.187	0.236	79
Participants	MT	Vertebral	1.451	3	0.694	1.000	151
Participants	MT	Sternal	1.134	3	0.769	0.528	151
Participants	LT	Vertebral	2.060	3	0.560	0.700	154
Participants	LT	Sternal	1.906	3	0.592	0.438	154
Participants	MC	Vertebral	1.647	3	0.649	0.868	164
Participants	MC	Sternal	2.157	2	0.340	0.354	164

Table 6.42: Results of $\chi2$ test for association between knife tip shape and vertebral/sternal wall projection size for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.4.7 Margin regularity

The control group has a significant association ($p<0.05$) between margin regularity and knife tip shape at the vertebral wall for the medial tip and main channel, and at the sternal wall for the lateral tip (Table 6.43).

The participant group has a significant association ($p<0.05$) at both walls of the main channel, and the sternal wall of the lateral tip (Table 6.43).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	3.864	1	0.049	0.084	77
Control	MT	Sternal	0.209	1	0.648	1.000	78
Control	LT	Vertebral	2.245	1	0.134	0.156	77
Control	LT	Sternal	7.889	1	**0.005**	**0.026**	78
Control	MC	Vertebral	5.928	1	**0.015**	**0.025**	78
Control	MC	Sternal	14.826	1	**0.001**	**0.003**	78
Participants	MT	Vertebral	0.118	1	0.731	1.000	170
Participants	MT	Sternal	1.422	1	0.233	0.305	169
Participants	LT	Vertebral	3.111	2	0.211	0.179	172
Participants	LT	Sternal	4.413	1	**0.036**	**0.049**	168
Participants	MC	Vertebral	3.886	1	0.049	0.067	173
Participants	MC	Sternal	2.368	1	0.124	0.204	171

Table 6.43: Results of χ2 test for association between knife tip shape and margin regularity for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.4.8 Margin definition

For the control group, a significant association ($p<0.05$) exists between knife tip shape and margin definition for both vertebral margins at the lateral tip and the main channel, but no significant association ($p>0.05$) exists between these variables at the medial tip (Table 6.44)

The participant group shows significant association ($p<0.05$) between knife tip shape and the sternal margin in the main channel (Table 6.44).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	1.259	1	0.262	0.356	77
Control	MT	Sternal	0.023	1	0.880	1.000	79
Control	LT	Vertebral	4.942	1	**0.026**	**0.037**	79
Control	LT	Sternal	0.194	1	0.660	0.553	79
Control	MC	Vertebral	6.508	1	**0.011**	**0.019**	79
Control	MC	Sternal	3.119	1	0.077	0.110	79
Participants	MT	Vertebral	1.342	1	0.247	0.461	171
Participants	MT	Sternal	0.014	1	0.905	1.000	170
Participants	LT	Vertebral	3.501	1	0.061	0.070	170
Participants	LT	Sternal	3.431	1	0.064	0.103	168
Participants	MC	Vertebral	3.738	1	0.053	0.068	170
Participants	MC	Sternal	12.760	1	**0.001**	**0.001**	171

Table 6.44: Results of χ2 test for association between knife tip shape and margin definition for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.4.9 Margin splitting

No significant association ($p>0.05$) was recorded between knife tip shape type and margin splitting for any part of the kerf in either the control or the participant group (Table 6.45).

Group	Kerf location	Wall location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	0.145	1	0.704	1.000	76
Control	MT	Sternal	N/A	N/A	N/A	N/A	N/A
Control	LT	Vertebral	2.944	1	0.086	0.213	79
Control	LT	Sternal	1.779	1	0.182	0.279	78
Control	MC	Vertebral	N/A	N/A	N/A	N/A	N/A
Control	MC	Sternal	N/A	N/A	N/A	N/A	N/A
Participants	MT	Vertebral	0.207	1	0.649	1.000	173
Participants	MT	Sternal	0.138	1	0.710	1.000	172
Participants	LT	Vertebral	0.287	1	0.592	1.000	168
Participants	LT	Sternal	0.215	1	0.643	1.000	167
Participants	MC	Vertebral	0.069	1	0.793	1.000	171
Participants	MC	Sternal	N/A	N/A	N/A	N/A	N/A

Table 6.45: Results of χ2 test for association between knife tip shape and margin splitting for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/A - Not Applicable; in N/A cases no tests carried out as the result was constant.

6.4.10 Floor definition

No significant association (p>0.05) was recorded between knife tip shape type and floor definition for any part of the kerf in either group (Table 6.46).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	MT	5.712	2	0.058	0.044	76
Control	LT	0.002	1	0.966	1.000	61
Control	MC	1.067	2	0.587	0.458	79
Participants	MT	1.394	2	0.498	0.334	124
Participants	LT	0.733	1	0.489	0.304	119
Participants	MC	0.221	1	0.638	0.638	121

Table 6.46: Results of χ2 test for association between knife tip shape and for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.4.11 Floor width

No significant association ($p>0.05$) was recorded between knife tip shape and floor width for any part of the kerf in the control group (Table 6.47).

A significant association exists between the participant group kerf main channel and the knife tip shape (Table 6.47).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	1.026	1	0.311	0.391	51
Control	LT	2.080	1	0.149	0.195	59
Control	MC	3.909	2	0.142	0.139	70
Participants	MT	0.014	1	0.905	1.000	123
Participants	LT	0.375	2	0.829	1.000	119
Participants	MC	4.682	1	**0.030**	**0.045**	114

Table 6.47: Results of $\chi 2$ test for association between knife tip shape and for floor width control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.4.12 Floor splitting

No significant association ($p>0.05$) was recorded between knife tip shape and floor splitting for any part of the kerf in either group (Table 6.48)

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	0.221	1	0.638	1.000	52
Control	LT	N/A	N/A	N/A	N/A	N/A
Control	MC	0.326	1	0.568	1.000	70
Participants	MT	0.350	1	0.554	1.000	127
Participants	LT	0.168	2	0.919	1.000	118
Participants	MC	1.456	1	0.228	0.605	119

Table 6.48: Results of $\chi 2$ test for association between knife tip shape type and floor splitting for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/A - Not Applicable; in N/A cases no tests carried out as the result was constant.

6.4.13 Presence of debris

No significant association ($p>0.05$) exists for the control group for any part of the kerf (Table 6.49).

The participant group demonstrates a significant association ($p<0.05$) for the lateral tip only (Table 6.49).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	0.180	1	0.893	1.000	76
Control	LT	1.506	1	0.220	0.393	77
Control	MC	2.162	1	0.141	0.328	80
Participants	MT	1.860	2	0.394	0.338	169
Participants	LT	6.148	1	**0.013**	**0.017**	169
Participants	MC	0.155	1	0.694	1.000	170

Table 6.49: Results of $\chi 2$ test for association between knife tip shape and the presence of debris for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.4.14 Debris fragment type

The control group shows no significant association (p>0.05) between knife tip shape and the debris fragment type. The participant group kerfs both exhibit significant association (p<0.05) between the knife tip shape and the type of debris fragments for the main channel and the lateral tip (Table 6.50).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	0.452	2	0.798	1.000	77
Control	LT	6.039	3	0.110	0.116	77
Control	MC	4.222	3	0.238	0.163	81
Participants	MT	1.110	3	0.775	0.658	168
Participants	LT	10.900	3	**0.012**	**0.015**	164
Participants	MC	19.827	4	**0.001**	**0.013**	168

Table 6.50: Results of $\chi 2$ test for association between knife tip shape and the type of debris fragment for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.4.15 Debris fragment size

The control group shows no significant association ($p>0.05$) between knife tip shape and the debris fragment type. The participant group kerfs both exhibit significant association ($p<0.05$) between the knife tip shape and the size of debris fragments for the lateral tip only (Table 6.51).

Group	Kerf location	$\chi 2$	df	p value	Fisher's exact test	N
Control	MT	5.091	3	0.165	0.228	77
Control	LT	3.222	3	0.359	0.218	77
Control	MC	3.526	3	0.317	0.237	81
Participants	MT	2.161	3	0.540	0.514	168
Participants	LT	13.146	3	**0.004**	0.004	164
Participants	MC	3.796	3	0.284	0.272	169

Table 6.51: Results of $\chi 2$ test for association between knife tip shape and the size of debris fragment for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel and N/C = not calculated.

6.4.16 Debris material

Neither the control group nor the participant group shows a significant association ($p<0.05$) for any part of the kerf between knife tip shape and the type of debris material (Table 6.52).

Group	Kerf location	χ2	df	p value	Fisher's exact test	N
Control	MT	0.319	3	0.956	1.000	77
Control	LT	6.317	4	0.177	0.199	76
Control	MC	6.182	3	0.103	0.151	78
Participants	MT	2.619	4	0.623	0.525	167
Participants	LT	7.657	3	0.054	0.013	165
Participants	MC	4.739	5	0.449	0.372	171

Table 6.52: Results of χ2 test for association between knife tip shape and the type of debris material for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.4.17 Lateral ridging

Neither the control nor the participant group had significant associations ($p<0.05$) between knife tip shape and lateral ridging at any location in the kerf (Table 6.53).

Group	Kerf location	Margin location	χ2	df	p value	Fisher's exact test	N
Control	MT	Vertebral	2.351	1	0.125	0.186	79
Control	MT	Sternal	1.811	1	0.178	0.330	78
Control	LT	Vertebral	1.883	1	0.170	0.328	80
Control	LT	Sternal	3.924	1	0.048	0.108	80
Control	MC	Vertebral	1.771	1	0.183	0.233	80
Control	MC	Sternal	0.127	1	0.722	1.000	80
Participants	MT	Vertebral	0.022	1	0.881	1.000	177
Participants	MT	Sternal	1.006	1	0.316	0.330	176
Participants	LT	Vertebral	1.536	1	0.215	0.367	173
Participants	LT	Sternal	0.903	1	0.342	0.466	173
Participants	MC	Vertebral	0.252	1	0.616	1.000	176
Participants	MC	Sternal	0.984	1	0.321	0.354	176

Table 6.53: Results of χ2 test for association between knife tip shape and the presence of lateral ridging at the sternal/vertebral margins, for control and participant groups. MT = medial tip; LT= lateral tip; MC = main channel.

6.4.18 Summary

The significant associations ($p<0.05$) identified between knife tip shape and kerf features have been summarised in Table 6.54. There are 4 features that have significant associations with the knife type for the control group, and 10 features for the participant group. The greatest number of significant associations is at the main channel, followed by the lateral tip. There are no significant associations ($p>0.05$) with the medial tip for the participant group.

Experiment group	Control	Participants	Control	Participants	Control	Participants
Kerf location	*Medial tip*	*Medial tip*	*Lateral tip*	*Lateral tip*	*Main channel*	*Main channel*
Kerf features						
Tip shape						
Bifurcation						
X-Section						
V. Gradient				●		
S. Gradient						●
V. No.wall projections						
S. No. wall projections						
V. Projection size						
S. Projection Size						●
V. Margin Regularity					●	
S. Margin Regularity			●	●		
V. Margin Definition			●		●	
S. Margin Definition						●
V. Margin Splitting						
S. Margin Splitting						
Floor Definition						
Floor Splitting						
Floor Width						●
Debris presence				●		
Debris fragment type				●		●
Debris size				●		
Debris material						
V. Lateral Ridging						
S. Lateral Ridging						

Table 6.54: Summary table showing significant associations by group, kerf location and kerf feature. Blank cells have no significant association. Black circles mark significant associations.

Chapter 7 Discussion

7.1 Tip shape

The overall marginal shape of the each tip was noted. Several different shapes were observed including square, rounded, tapered, bulbous and flared or open ended tips, as well as a range of irregular shapes (Figure 7.1). No significant association between tip shape and knife class, tip shape and knife sub-class or kerf tip shape and knife tip shape was recorded for either the control group or the participant group at any part of the kerf. In Tennick *et al.* (2008), tip shape was shown to have a significant association (χ^2 = 18.267, df=6, p=0.006) with the blade type (scalloped, serrated, fine). Tennick *et al.* (2008) used knives of different sizes and shapes, in contrast to the current study which used 9 blades of a similar size and shape. The lack of association between the shape of the tips and the knife type could therefore be attributed to the similarity of the knives used, and having similar class features in terms of size and shape. Slight variations in application of the knife against the bone by manual operators may also have an effect, combined with the variation in mark placement and relative bone topography. The importance of viewing samples at a range of angles under oblique lighting was particularly important as the subjective assessment of shape has the potential to be changed dramatically by shifting the angle of the oblique light source. Differentiating between kerf margin shape and deposited surface debris at the termini was also challenging when attempting to assess the overall shape. Symes *et al.* (2010) documents a single tip characteristic for saws known as kerf flare, where the kerf flares outwards; this relates to increased movement at the handle end of the blade. The absence of any significant relationship between tip shape and knife blades at either tip indicates that this finding cannot be readily applied to knife blades. This is important as knife blades with teeth can be considered like saws (Symes *et al*.

2010) when used in a reciprocating motion. In drawing comparisons, Symes (1992) examines only one serrated blade with a range of saws. Previous work (Symes 1992, Symes *et al.* 2010) discusses saw “set”; the sample knives here have no set, which could possibly account for the absence of significant features, although flare is found across a variety of saw set types (Symes et al, 2010). The length and flexibility of saws, when compared to the shorter, rigid knife structure which less prone to bending movement may also be a factor to consider.

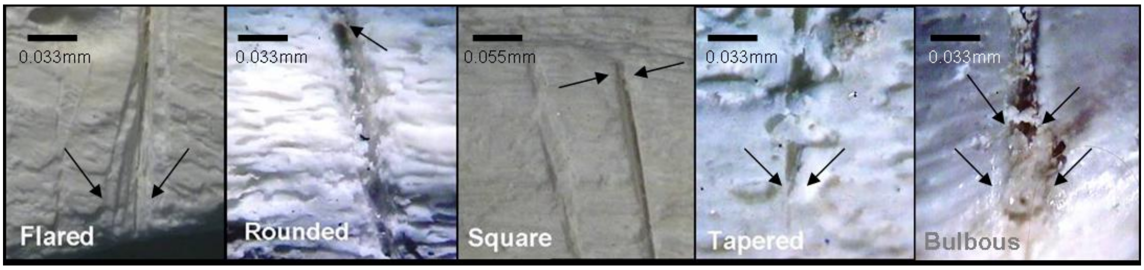

Figure 7.1 Showing variations of tip shape, at magnifications of x180 to x300 on a Projectina Comparison Macroscope:

7.2 Bifurcation

Bifurcation showed no significant association with the control group kerf tips, but demonstrated a significant association for both tips in the participant group; this was true for both class and sub-class knife variables. No significant association existed between bifurcation and knife tip shape. On examination of class features, both medial and lateral tips have similar incidences of bifurcation for each knife type. At the medial tip 21% of scalloped blades produced bifurcated tips, in comparison to 26.2% at the lateral tip. Fine and serrated blades have similar overall incidences of bifurcation, 5.6% of fine and serrated blades produce bifurcated tips. At the lateral tip, 8.9% of serrated kerfs produce bifurcation, and 7.3% of fine-edged blades produced bifurcated tips. When examining sub-class features, Scalloped Blade 1 (SC1) kerfs had the greatest number of bifurcated tips at the medial tip, and Scalloped Blade 2 (SC2) kerfs were most commonly bifurcated at the lateral tip. Bifurcation was less frequent amongst the serrated and fine-bladed knives. In the participants group, only 14.5% (n=172) of kerfs exhibited bifurcation at the lateral tip, and 11.2% at the medial tip. Scalloped blade 3 (SC3) has more TPI than SC2 and SC1; it is suggested that the increased number of teeth give better grip on the bone surface and allow effective penetration of the blade. SC1 and SC2, with fewer TPI, have fewer points to contact the bone surface at any one time and therefore may be more likely to bounce or skip on incision and excision from the bone, moving the blade position in relation to the kerf. The control group has no significant association, and although bifurcation was recorded, the lack of association may be related to how the knife is applied to the bone such as the angle or force of the cut, which may be more consistent in a single individual than across a large group. By varying the knife operators, the angle of the blade may be subject to variations in position, creating more opportunities for bifurcation. Serrated blades have a better grip on the surface with the greatest number of TPI, and fine blades have a single sharpened blade that have uninterrupted contact with the bone surface and therefore less likely to change blade trajectory on incision and excision of the blade. Symes *et al.* (2010) documents a tip feature in saw analysis; known as kerf flare. Symes *et al.* (2010) suggest that the presence of flare is present in the kerf at the same side as the handle part of the blade for saws. In knives, the bifurcation of tips is found at both ends of the kerf in the participant group, and therefore not related to the orientation of the blade handle. The depth of blade penetration may have an effect on the presence of the characteristic; further work could be done to establish whether it is shallower marks exhibiting bifurcation as the blade has more freedom of movement. Although bifurcation is present more often in scalloped blades, it is still only present in 20-26% of the sample and is not unique to this blade class. The absence of any significant association between bifurcation and knife variables for the control group could be as a result of a smaller sample size, or increased consistency of force and angle as a result of a single operator. This result may indicate that previous findings by Symes *et al.* (2010) in relation to saws and the presence of tip features at one end of the kerf to indicate the handle end of the knife blade does not apply to knives in this case. This means that the application of kerf features previously observed in saws may not always be appropriate in the analysis of knife kerfs; thus highlighting the need and importance for work and terminology specific to knife blade kerfs as provided by the current thesis.

7.3 Cross-section shape

Cross-section shape exhibits significant relationships with class and sub-class blade features, but not with blade tip shape. Class features demonstrated a significant association with the main channel of the kerf for the control group only. Fine-edged blades produced V-shaped kerfs for 80% of kerfs made with fin blades. Scalloped blades produced a wider range of cross-section shapes, with 68% of marks in the U, square-bottomed or other profile shapes, and only 32% of marks had V-shaped kerfs. Around 54% of serrated blades made V-shaped kerfs, 25% produced U-shaped kerfs and 26% of kerfs were classified as “other” cross-sectional shapes.

Symes et al. (2010) suggest that serrated blades produce narrow v-shaped profiles, and work done by others (Potts and Shipman, 1981; Shipman, 1983; Greenfield, 1999; Blumenschine *et al*., 1996; and Alunni-Perret *et al.* 2005) examining fine-edged blades also mention V-shaped profiles as the most common. The results support existing trends to a degree, however it is clear that a wider variety of shapes is possible; this includes U-shaped kerfs which are commonly attributed to stone tools (Potts and Shipman, 1981; Shipman, 1983; Greenfield, 1999; and Blumenschine *et al*., 1996). Scalloped blades however do not follow this trend, 50% of kerfs have a cross sectional shape classed as “other”, and another 18% of the kerfs were U or square-bottomed profiles. As many of the incisions were shallow, the blade points can move more freely over the surface of the bone and are more subject to changes in trajectory or surface skipping, and subsequent teeth travelling over the bone surface causing variation to the cross-sectional shape. This is the first time serrated blades have been differentiated and studied according to tooth size and clearly the TPI/PPI has an effect on the kerf features as serrated blades with more TPI/PPI produce more V-shaped kerfs than scalloped blades, but fewer than fine-edged blades.

When examining sub-class blade features, only the group of kerfs produced by the participants showed a significant association between kerf cross-section and the knife sub-class for all parts of the kerf. For the lateral tip, serrated blade 1 (SR1) and serrated blade 2 (SR2) exhibited the lowest frequencies for the cross-sectional shape class of ‘other’. There were no occurrences for SR1, and a single occurrence for SR2. Serrated blade 3 (SR3) had the greatest number of cross-section shapes classified as ‘other’. Fine blades had the fewest observed incidences of cross-sections classified as ‘other’. Although the results give a significant value, the inability of SPSS to calculate a result for the Fishers exact test, combined with small number of cases in parts of the table means that the result requires further investigation.

V-shaped blades were the most common cross-sectional shape observed, in line with existing knowledge (Potts and Shipman, 1981; Shipman, 1983; Greenfield, 1999; and Blumenschine *et al*., 1996). Lewis (2008) states that V-shaped kerfs are characteristic of knife blades and can be used to distinguish between knife kerfs and more variable sword kerf cross-sections; however the variation in kerf shapes for knives across the control and participant groups indicates that this would not be a reliable diagnostic criterion for distinguishing swords and knives. There were a variety of other shapes observed in addition to V, U and square bottomed profile shapes, and for the purposes of this study they were categorised as “other”. By expanding this broad term to reflect some of the variation, there may be more useful cross-section shapes that have a relationship with the blade shape.

It also highlights the variety of shapes encountered when using a number of manual operators. Sometimes the cross-sectional shape was difficult to observe with the light microscope. Digital microscopy may allow a closer view of the bone, but the difficulty in observing some features highlights a potential advantage of using casting compounds in order to see the profile shape; the use of digital microscopy and 3D scanning software could still allow the mark to be viewed in three dimensions, without the difficulty of casting it. Many cut marks were extremely narrow, and the practicalities of casting incision marks on bone for forensic purposes have not been widely published. The work to date on serrated blades is extremely limited; Symes (1992) examined one in comparison with saws, and Thompson and Inglis (2008) used one serrated blade to examine stab wounds in bone. Scalloped blades are not defined in previous studies at all. The results indicate that there may be potential to distinguish between blade classes, as scalloped blades marks produce more irregular cross-section shapes than the other blade types. The results also challenge existing knowledge by highlighting that scalloped and serrated knives can produce a range of shapes that do not conform to previous published results.

7.4 Wall gradient

Significant associations have been recorded between knife class and the vertebral wall gradient at the lateral tip for the control group, and at the main channel for both control and participant groups. There are also significant associations between sternal wall gradient and knife class at the medial tip for both control and participant groups, and at the main channel for the control group only.

The walls corresponding to the cutting edge of the blade (vertebral wall) in the control group main channel are mostly steep or very steep (96% of serrated blades kerfs and 92% of fine blade kerfs had steep or very step walls). Scalloped blades however had a wider range of wall gradients, with only 67% of scalloped kerfs exhibiting steep or very steep vertebral walls, and another 30% with shallow or very shallow walls, in comparison to just 4% of fine and serrated kerfs.

Once again scalloped blades produce different overall wall slopes to fine and serrated blades. Fine blade cutting edges have the greatest level of contact with the bone, followed by serrated and scalloped blades. Increased levels of contact may allow for more consistent movement over and through the bone; once again the nature of teeth in the scalloped blades may cause them to skip and chatter over the surface therefore varying the angle of contact and potentially the depth to which the blade can penetrate; if the blade cannot gain purchase in the surface this could cause variation in the slope of the wall.

At the sternal main channel wall, the walls are much more consistently steep or very steep across the blade classes (89% of fine kerfs, 88.5% scalloped kerfs and 91% serrated kerfs). This corresponds to the back of the blade; in fine blades the blade is ground on both sides of the knife, but the patterned blades have indented teeth on the knife cutting edge and a flat back edge. Future analysis could try and compare the wall slopes on corresponding walls with the cross-section shape of the knives; it is not possible with the data in its current form but could be explored further. Many of the knives have bevelled edges which may also influence the slope of the walls. Another factor to consider is the variation caused by human operators in the slope of the walls and the angle of application to the bone. For the control group the potential range of influence is much smaller than the participant group.

The participant group only showed a significant result at the main channel for the vertebral wall slope. This corresponds to the back of the blade rather than the principal cutting edge. For this group, the scalloped edges produce the greatest number of steep and very steep slopes (87%) followed by fine-edged blades (77%). In this group serrated blade kerfs produced steep or very steep vertebral wall slopes in 63% of their marks, and 37% were shallow or very shallow. This wall corresponds to the back of the blade; the scalloped blades have shallower bevels than the rest of the knife classes, and SC3 has no bevel on the back of the blade at all, resulting in steeper walls. The greater variety of slopes for the back of the blade may be the result of the different operators and the way in which they produced the marks. The blade handles may have had an effect on the way in which the knife was held and hence the angle at which it enters the bone; the scalloped and fine blades have flat handles; the serrated blades have ergonomically designed handles which slope; the slope of the handle combined with variation in grip could explain the broad range of wall slopes. The absence of any significant relationship at the sternal wall could be a result of the greater variety of forces and angles produced by the participants and the action of the cutting edge; although the result is not statistically significant, the frequencies of steep and very steep wall slopes are all greater than the vertebral wall for all blade types (F=89%, SC=89%, SR=91%).

The sternal wall slope at the main channel exhibited a significant relationship for the participant group; this corresponds to the cutting edge of the knife blade. Fine and serrated blades both have the greatest frequency of very steep walls (65%); scalloped blades have the greatest frequency of wall slopes at steep (31.7%), and no gradient (8.3%) when compared to the other knife classes. There is a greater variety of wall slopes across all blade types in the participant group when compared to the control group. There are also kerfs present with no sternal gradient; this is unique to the scalloped and serrated knife classes. It is possible that these kerfs are the result of varying knife interactions with the bone, perhaps as a result of scraping the bone surface, which is more likely with teeth that can bounce and chatter on contact. Fine and serrated blades produce steeper walls than scalloped blades; the relative thickness of the blades at the cutting edges may also have an impact as the scalloped blades are thicker at the cutting edge than the fine and serrated blades.

The control group had significant associations between knife sub class and wall gradient at both walls of the main channel, the sternal wall of the medial tip, and the vertebral wall of lateral tip. The main channel sternal wall for the control group was the wall created by the back of the blade, which has points but no pattern. The scalloped blade class for the control group main channels all produced the greatest frequency of very steep kerf walls (SC1 = 70%, SC2 = 75% and SC3 = 67%). The serrated blade class produced steep kerf walls more frequently (SR1 = 44.4%, SR2 = 56%, SR3= 44.4%). The fine blade class a mixed profile; 56% of F1 kerfs had a steep wall, and the 44% were very steep, 45% of F2 kerfs were steep, 33% were very shallow and the rest are equally split between shallow and very steep. The F3 kerfs produced 70% steep walls, and 30% very steep.

The scalloped blades have a flat back (SC3) or gentle, tall bevel (SC1 and SC2). This shape may contribute to the formation of a very steeply sloped wall. The serrated blades have smaller, steeper bevels than the scalloped knives and therefore produced a kerf with a more gradual slope. The fine edged blades each had a small steep bevel, continuous with a larger shallower bevel. Fine edged blades have similar frequencies of steep walls as the serrated blades; F2 was the only blade to produce shallower walls. The fine knives have similar blade features to one another, so other factors may contribute to the fluctuating shape, such as the shape of the bone, the force and angle of the blow. The fine ground edge, with steep even grind on both sides may act as a better pivot than patterned blades with teeth, and so may be more subject to minor fluctuations in operator variation (such as the angle of the blade) within the kerf.

The vertebral wall for the control group was the wall facing the front part of the blade, including the teeth for serrated and scalloped blades. Steep walls were the most frequent for the fine blade class (F1= 66.7%, F2= 55.6%, F3 = 90%), and for SR1 (67%). SR2 and SR3 had the greatest frequency of very steep walls (56% and 67%, respectively). SC1 produced 60% of kerfs with steep walls, and 40% with very steep walls. SC2 produced walls for every slope, and a single occurrence of no wall in the vertebral plane. SC3 also produced a variety of wall slopes, from very shallow to very steep.

Fine blades produced a steeper wall at the main cutting edge than at the rear of the blade. The relatively symmetrical appearance of the cutting edges at either side of the blade would not account for differences in the level of slope; therefore the angle of the blade in relation to the bone must also have an effect. Scalloped blades produced a range of slopes at the cutting edge; SC2 and SC3 had broader blades with a deeper tooth bevel than SC1 and the passage of the teeth through the bone creates a greater range of wall slopes. SC1 has a thinner cutting edge, with shallower bevels, possibly producing a more consistent wall shape. The serrated blades also had very shallow bevels and closely packed teeth, effectively slicing through the bone to create a steep wall.

The sub-class participant group exhibited a significant association with only the vertebral wall of the main channel. As the ribs for the participant group came from right side, the vertebral wall faces the back part of the blade and therefore corresponds to the rear face of the patterned edge. This part of the blade is more consistent in form across blade class (as described previously for the control group), and therefore by introducing a range of knife operators using a range of different angles and forces to apply the blade to the bone, the rear, flatter part of the blade may produce a more consistent wall morphology then the movement of teeth through the bone at the sternal plane. Fine blade 1 and 3 produced very steep walls, (64.5% and 45.5%, respectively), F2 produced a range of wall slopes at similar frequencies. Scalloped blade SC1 produced the greatest number of very steep walls (58%), SC2 and SC3 had higher proportions of steep walls (63% and 80%). Serrated blades produced a much greater range of slopes in the participant group, likely to be a result of the greater range of forces and angles used by a range of participants.

The vertebral and sternal margins of the lateral tip were also the locations of a significant association between blade type and knife type. They show similar trends to the main channel, with a variety of slope types for each knife, particularly fine blades. The lateral tip may be more likely to provide associations between knife type and wall gradient because it has the potential for more contact with the blade during incision and excision than the medial tip, but the increased contact may also result in a greater variety of slopes recorded in response to minor operator changes of angle. For the control group, the vertebral medial tip was the location of another significant association; steep and very steep walls were the most common across all blades. Fine knives had steep walls most frequently in their kerfs (F1=67%, F2=33%, and F3 =42.9%). SC1 kerfs were split evenly between steep and very steep, SC2 had 37.5% of kerfs classified as very steep; SC3 had no very steep walls, and 50% were steep. SR2 (75%) and SR3 (50%) had kerfs with very steep walls; SR3 had steep kerf walls as the most frequent (62.5%). All knives (with the exception of SC1) had walls at a range of gradients. The sternal lateral tip was also the location of a significant association; once again, there was a slight trend to the steeper walls for all kerfs, with the exception of F2, where 44% of kerfs are very shallow.

When the blunt tip of SC3 was compared to the pointed tips of the rest of the knife blades, only the vertebral wall slope at the lateral tip in the participant group, and the sternal wall of the main channel demonstrated a significant relationship. At the lateral tip the blunt blade produces no very steep walls; 78% of the walls are steep and no walls are very steep or shallow. For the pointed blades, there are comparable amounts of steep (37%) and very steep (35%) wall slopes. At the main channel the blunt blade produced 80% of kerfs with steep walls and only 10% with very steep slopes, compared to the pointed blades with 59% very steep and 30% steep slopes produced. The rounded blade is also thicker at the tip than all of the pointed blades, and front of the blade is more blunt. The blunt blade also has a steeper bevel on the cutting edge than the pointed blades and hence this may result in slightly shallower walls; however this does not account for the rest of the blade passing through the bone. What cannot be ascertained is the depth to which each knife entered and exited the bone; therefore the level of contact between the knife and each kerf may vary for each kerf. In future studies it may be useful to monitor this in order to consider its effect on results. The sample size for the blunt blades is much smaller than the pointed blades; examining a larger sample size and looking at a wider range of tip shapes or more specific aspects of the knife tip could be useful work for the future and might clarify any relationships between knife tip shape and kerf features.

The classifications of wall slope are not measured, but gauged by eye; there is therefore some potential for cross-over between categories. The trends exhibited in the main channel for the control marks show potential for broad classification of blades according to blade shape. The tips show a greater range and may be more drastically influenced by minor operator adjustments during blade use, as well as potentially being more difficult to examine; narrow kerfs with tapered or rounded tips in particular are challenging to observe. The depth of height of the kerf can also present challenges; deep kerfs that prevent observation of the floor prevent a reliable assessment of gradient, and very shallow kerfs can also be difficult get enough contrast to assess the slope. Multiple operators combined with the cutting edge of the knife, introduces more variation, but the flat section of the blade is responsible for more consistency in the participant group. Even if some aspects of blade shape could be reflected in bone, with different operators, it could be useful for investigators. Digital microscopy (such as that employed by Boschin and Crezzini, (2011)) can provide 3D surface mapping and possible quantification of this variable.

7.5 Wall projection frequency

Knife class features had significant relationships with wall projection frequency at the vertebral wall for the lateral tip in the control group and the main channel in the participant group. More relationships were found at the sternal wall at the main channel for both the control and participant groups. The participant group also exhibited an association between knife class and the number of wall projections at the lateral tip.

At the lateral tip vertebral wall for the control group (which corresponds to the main cutting edge), the fine blade class produced the fewest wall projections (90.5% of fine kerfs had no wall projections at all). In scalloped blades, 30% of kerfs had wall projections; 56% of serrated blade kerfs had wall projections, compared to just 10% in the fine blades. At the sternal wall main channel, the fine blades in the control group had the greatest number of kerfs with no wall projections (50%) and the fewest with many wall projections (10.7%). Serrated kerfs contained projections more frequently (86%) than scalloped blades (60%).

For the participant group at the vertebral wall of the main channel (corresponding to the back of the blade), scalloped blades produced the greatest number of kerfs with many projections (27%) and the smallest number of kerfs with few projections (22%). Serrated blades had the greatest number of kerfs with few projections (32%) but also contained kerfs with many projections (24.5%). Fine blades produced a relatively small proportion of kerfs with many projections (5.9%). At the sternal wall of the main channel, the participant group showed the same trend as the vertebral wall for fine blades, with fewest kerfs with many projections (7.8%) and the highest incidence of kerfs with no projections at all (49%). Scalloped and serrated blades produced equivalent frequencies of many projections (42%), whilst serrated blades had the highest proportion of kerfs containing few projections (45%), and the lowest incidence of kerfs with no projections at all (13%). At the lateral tip, fine blades produced fewest kerfs with many projections (9%) and the highest frequency of kerfs with no projections (78%). Serrated blades have the highest incidence of kerfs with projections (62%) and the smallest number of kerfs with no projections (38%)

Fine blades produced significantly more kerfs with no projections than the patterned blades. The presence of teeth against the surface of the bone may be more likely to leave irregularities in the kerf walls for the scalloped and serrated blades; serrated blades have the greatest number of projections overall in the participant and control groups in all areas of the kerf; the fact that serrated blades have a higher number of TPI/PPI may account for this, as there are more opportunities for the points of the blade to interact with the bone, and concave teeth between the points to facilitate an irregular surface. Serrated and scalloped blades tended to have more wall projections however some fine blade kerfs also exhibited wall projections. The angle and force of the blade may also have an impact on this particular kerf characteristic; there may be scope for further work in this area. Although there are areas of overlap, the presence or absence of wall projections may prove to be useful guidance for class features when used in conjunction with other criteria to give context. Refining the criteria for future analysis may also help; wall projections are differentiated from on whether the feature is attached to the kerf wall (or not). With smaller projections, this differentiation may be problematic; it could be possible for debris close to the walls and wall projections to be misclassified.

The vertebral and sternal walls of the main channel both showed a significant association with knife sub-class for the control group. For vertebral walls, fine blades have higher frequencies of kerfs with few or no projections; 56% of F1 kerfs have small wall projections, and 22% have none; 50% of F2 kerfs had small projections, and 38% had none; F3 had the highest number of kerfs with no wall projections (70%), and 30% had small projections.

50% of SC1 kerfs had large projections, and 40% had small. SC2 and SC3 had higher proportions of small projections. No large projections were present in SR1 kerfs, but 90% of kerfs had small projections. All SR2 kerfs had projections; 67% were small, and 37% were large. For the sternal wall, Serrated blade kerfs had the highest frequency of large wall projections (SR1=90%, SR2=56%, SR3= 56%). SC1 kerfs had large (50%) or small (40%) wall projections, SC2 and SC3 had much lower frequencies of large projections (0%, and 16.7%) in addition to small projections; most often no projections at all (63% and 67%) were observed.

There is a large degree of overlap in sub-classes, and similarities in terms of some of the relative frequencies for the vertebral and sternal walls. Small projections are present in all blade types. The absence of projections could be diagnostic of F3, SC2 or SC3; large projections could indicate SC1 or SR2, and small projections are present in most of the kerfs.

The main channel vertebral wall in the participant group was the location for a significant association between knife sub-class and wall projections. As with trends in the control group, fine blade kerfs had more kerfs with no projections (F1 = 61%, F3 = 55%) or small projections (F2 = 67%). Scalloped blade kerfs most frequently had no projections, but all exhibited both large and small projections. Serrated blades show few clear trends; SR3 kerfs had a higher proportion of large projections (44%). Although the participant group shares some trends with the control group such as fine blade kerfs with few or no projections, the degrees of overlap of categories in this criterion are such that it cannot be confidently used as a predictor of knife sub-class.

7.6 Wall projection size

For class knife features, the control group had only one significant relationship with projection size, in the vertebral lateral tip. The serrated blade class produced more large projections (in 34% of serrated kerfs) than scalloped

(13%) and fine blades (0%). Scalloped blades produced more small wall projections in their kerfs (21.7% than serrated (19.2%) and fine (9.5%) blades.

The participant group has relationships between blade class and the sternal wall projections size at the main channel and lateral tip. At the lateral tip, serrated blade kerfs have the greatest frequency of large projections (34%); scalloped blades have highest proportion of kerfs with small wall projections (24%) and fine blades have the smallest number of kerfs with small or large wall projections (11% and 6.5% respectively). At the main channel, the trends were very similar; the serrated blade kerfs contained more large wall projections (36%) than the other two knife blade classes, and the scalloped kerfs more frequently contained small wall projections (33%) and fine blades produced the fewest small (25.5%) and large (17.6%) wall projections of all knife classes.

As with the presence of wall projections, the significant relationships in both groups correspond to the wall which faces the main cutting edge of the blade. The serrated blades seem to produce larger wall projections more frequently than the scalloped blades, which is surprising given that the scalloped blades have larger teeth. It could be that because the scalloped blades are wider at the cutting edge, with wide teeth and broader thicker points, that any projecting bone is worn away or crushed by the patterned blade edge during movement through the kerf. All serrated blades examined had a wave in the tooth pattern; each wave has tooth points at different heights, so when applied to a surface, it could be possible the large wall projections are a result of the wave in the blade. Scalloped blade tooth points are more linear and therefore may all contact the surface at the same height, potentially removing more of the bone surface, creating smaller projections. As wall projection characteristics are novel in their application to kerf analysis, further exploration of this variable may be useful if the fragment sizes can measured and quantified, and in particular, if the projections are found to be comparable to tooth or wave features on the knife blade.

Knife type and wall projection size had a significant association with knife sub class at both walls of the main channel for the control group. At the vertebral wall, F1 produced kerfs with small (44%) or large (34%) projections, but never combined sizes in the same kerf; F2 had equal proportions of large or small projections in the kerfs, and 12% of F2 kerfs exhibited projections of both sizes. F3 produced kerfs with no large projections in isolation, a single kerf with small and large projections, and small projections (20%). SC1 blades resulted in kerfs with small (30%) and large projections (20%), and the largest frequency of kerfs with a combination of sizes (40%). SC2 produced the greatest frequency of large projections for scalloped blades (37.5%) and SC3 kerfs had an increased frequency of wall projections in comparison to other scalloped knives (34%). SR1 knives produced kerfs with similar frequencies of small and large projections (44% and 33%), whereas SR2 had a greater frequency of large projections than other serrated blades (67%). SR3 has the largest frequency of combined wall projections in the kerf.

For the sternal wall, F1 had a greater frequency of small (55.6%) and large (22.2%) wall projections as discrete groups than the other two fine blades. SC1 had the largest frequency of combined wall projection sizes for scalloped blades, and SC3 had no kerfs with large projections. Of the serrated class, SR1 blades had the largest frequency of small projections (44%), SR2 blades had no small projections alone, but 22% of kerfs had combined wall projections; 67% of SR2 blades produce large fragments. SR3 kerfs most commonly contain combined wall projection sizes (56%).

Although the blades show some different traits within their sub-class categories, unlike the wall gradient, there are no clear morphological features of the knife sub-class to attribute to the variety and combination of results recorded. Although a significant result was recorded for the lateral tip and main channel of the participant group; no Fisher exact test result could be calculated and so a larger sample is needed to confirm whether the sternal wall projection size can be linked to sub class features.   The fact that significant results for control and participant groups relate to the main cutting edge of the blade may give an indication that quantitative assessment of wall projection size could be investigated further.

7.7 Margin regularity

Class knife features had significant associations with the control group main channel vertebral margin regularity. Fine blades produce regular margins most frequently (89%), in comparison to serrated blade kerfs, of which around half (54%) have regular margins. Scalloped blades produce the fewest kerfs with regular margins (39%). About 61% of scalloped kerfs have irregular vertebral margins, compared to 46% of serrated kerfs and just 7% of fine kerfs. At the medial tip, the sternal margin shows a significant association with knife class. Fine blades produce irregular margins least frequently (6.9%) when compared to scalloped knives (27%) and serrated knives (40%).

For the participant group, only the tips show any significant relationships between knife class and margin regularity. At the medial tip vertebral wall, scalloped blades produced more frequent regular margins (85%) than fine or serrated blades. At the medial tip sternal wall, fine blade kerfs were most frequently regular (83%) in comparison to scalloped (62%) and serrated (68%). Scalloped blades produced the most frequent irregular margins (38%). The lateral tip sternal wall had more regular fine kerfs (81.5%). Scalloped and Serrated blades had more frequent incidences of irregular margins than the fine blades (SC=47%, SR=37.5%, F= 18.5%).

Patterned blades in the control and participant groups produce more regular margins than serrated and scalloped blades at both sides of the kerf because the fine blades were uniformly regular on both sides of the blade. In the control group the vertebral margins face the patterned edge of the knife blades and thus produce more irregular margins, particularly for scalloped blades. This trend is not reflected in the main channel of the participant groups, only in the tips. Once reason for this may be the context of the kerf and the subjective nature of the criteria; as the tips are at the ends of the kerf and the area is smaller, deviation from a linear from may be more readily visible over a small area, then when examining the greater area that makes up the main channel. It may be useful further work to examine the tips in more detail to see if the irregularity at the margins corresponds to specific blade teeth characteristics, morphology and measurements. It could also be useful to examine the relative lengths of the marks; a subtle curve in a longer mark may not be classified as irregular, whereas a curve in a shorter mark may be more easily classified as irregular. The variation in application of the knife to the bone by different participants in terms of force and angle could also be explored as it may have an effect on the margin appearance.

Main channel margin regularity at the vertebral margin shows a strong association with knife sub-class for the control kerfs only. F1 and F3 had consistently regular vertebral margins (100%), and F2 had 78% of kerfs classified as regular. Scalloped blades have a tendency towards irregular margins; SC2 and SC3 had irregular margins at 71% and 83% of their respective kerfs. SC1 produces regular and irregular margins at the same frequency (50%). SR1 and SR3 produced slightly more irregular than regular margins (56% frequency for each), and SR2 kerfs had consistently more regular (78%) than irregular classifications at the vertebral margin.

The sternal margin had an almost identical trend to the fine blades at the vertebral margin; F1 and F3 had 100% of kerfs classified as regular, and a slight increase in F2 regular kerfs (89%). At the vertebral margins, some scalloped blades had a greater frequency of irregular margins; at the sternal margin, the opposite is true. SC1 and SC2 have more regular margins (100% and 86%). SC3 was the exception, with 67% of kerfs classed as irregular. All of the serrated blades have more regular margins (SR1 = 89%, SR2 =78%, SR3 = 78%) at the sternal margin.

Margin regularity exhibited strong trends with knife sub-class; for the control group, vertebral margins faced the patterned part of the blade, and the sternal margins faced the back of the blade. Fine blades had the most symmetrical blades of the knife group tested, and the smooth nature of the cutting edge resulted in consistently (100%) regular margins for F1 and F3 at both margins of the kerf, a direct result of the blade symmetry and continuous contact of the blade with the bone surface to give a linear margin. F2 also produced high number of kerfs with regular margins, but there are no obvious morphological differences in the blades to account for the differences between F2 and the other two fine blades at either the vertebral or sternal margin. At the vertebral margin, SC2 and SC3 had predominantly irregular margins, whereas SC1 kerfs had both regular and irregular margins. One possible reason for the difference was tooth and point morphology; SC2 and SC3 had sharper teeth with deeper bevels. SC1 had rounded smoother points and shallower bevels in the teeth. The narrower, more angular nature of points in SC2 and SC3 travelling against bone during the formation of the kerf means less of the cutting edge has contact with the bone surface, making it more prone to skipping over the surface and producing a more irregular edge. This is a direct contrast to the teeth of SC1; a smoother, flatter point surface, and a much shallower bevel increased contact with the surface of the bone and has the potential to give more linear margin.

At the sternal margin, SC1 and SC2 kerfs had more regular margins than at the vertebral margin, as a result of the flat, unpatterned back of the blade. SC3 had more irregular margins; the key differences between this blade and SC1 and SC2 are the absence of a rear bevel, the shape of the blade tip, as well as the depth and sharpness of the teeth and points. The lack of bevel on SC3, combined with the rounded tip give the rear of the blade poor penetrative powers as it enters and leaves the bone. The other knives are pointed and bevelled at the tip, which assisted with penetration into the bone, thus creating a more regular, linear mark. The relationship between serrated blades and margin shape was less clear, as there was more variation in margin classification for SR1 and SR3, and SR2 had a higher frequency of defined margins. SR2 has the most teeth; SR1 and SR3 both have fine ground edges the blade tip, before the serrations begin, meaning that over the length of the blade, they have fewer teeth than SR2, and therefore had a poorer grip of the surface, resulting in irregular margins. Serrated blades generally produced more regular margins than scalloped blades in the sample. The two classes of patterned blade behaved differently; scalloped blades with their very large tooth pattern produced irregular margins, compared to serrated blades, with a much smaller, more compact tooth pattern, which produced a more regular edge. More teeth provide better grip on the surface and therefore serrated blades tend to produce a more linear margin. Scalloped blades with much fewer points have a poorer grip, and are therefore more likely to skip or 'chatter' across a surface, resulting in irregular margins.

The trends at the lateral vertebral margin for the control group are identical to the vertebral main channel for the fine blade class. SC1 produced more regular margins than at the main channel (100%), SC2 had more irregular margins and SC3 resulted in equal numbers of each. All serrated blades had more regular margins. The sternal linear margins had greater frequencies of defined sternal margins for blades in each class, with the exception of SC3. Increased regularity across blade classes at the lateral tip compared to the main channel could be an artefact of examining a smaller area, where changes in linearity may be subtle and only observable over a larger area. The participant group also exhibited similar traits at the lateral tip, with SC3 producing the greatest frequency of irregular margins (64%).

The sternal margin at the medial tip showed a significant association between margin regularity and blade tips shape. As with the main channel and lateral tip, all blades produced more regular margins, as a result of the flat back of the blade acting as a guide for the knife through the bone.

The lateral sternal tips in the control group had a significant association with blade tip shape. Kerfs produced by the pointed knife blades produce regular margins in 90% of cases, in comparison to the blunt blade which produced an even split (50% each) of regular and irregular margins.

At the main channel, both vertebral and sternal margins had significant associations with blade tip shape. At the vertebral margin, 83% of blunt kerfs are irregular, and only 17% were regular, in comparison to pointed kerfs which produced more regular margins (67%). At the sternal margins, 67% made by blunt blades were irregular, compared to just 10% of irregular margins for pointed kerfs.

The participant group exhibited significant relationships at the lateral tip sternal margin only. At the lateral tip sternal margin, blunt blades produced irregular margins in 64% of blunt blade kerfs, compared to 33% in pointed blades.

For the main channel and lateral tip in the control groups, and the lateral tip of the participant group, blunt blade kerfs have more irregular margins than pointed blade kerfs. The rounded end of the blade has less penetrative power in the bone and therefore may be more likely to move around or over the surface on contact; tapered or pointed tips allow better penetration of the bone by design and therefore may produce more linear or regular margins. The blunt sample in this analysis is small (it refers to only one knife blade, SC3) so increasing the sample size for future analysis would be beneficial.

The margins of the kerf certainly need to be examined more closely for their relationship with the morphology of the blade. As with previous characteristics, it is limited because although features are significant when made by the same operator, the introduction of different operators using the same knives does not have the same effect; however, scalloped blade 3 consistently produced irregular margins for both the control and participant groups, and this appears to be attributable to the difference in blade tip shape, as it is rounded, rather than tapered like the rest of the sample. It may be that sub-class differences are lost when marks are made by different users, but that larger class differences in morphology may have more potential for forensic investigation.

7.8 Margin definition

Class features had significant relationships with vertebral margin definition at the main channel in the control group. Fine blades produce more defined kerf margins (82%), followed by serrated kerfs (60%) and scalloped kerfs (52%). The participant group had significant associations with sternal margin definition at the main channel and medial tip. For the main channel, 75% of fine blade kerfs margins were defined, in comparison to just 33% of scalloped blade margins. Serrated blade kerfs have equal frequencies of defined and undefined kerfs. At the medial tip sternal wall, 78% of fine blade kerfs produced defined margins, followed by 65% of serrated kerfs and 54% of scalloped kerfs.

For the control and the participant groups, the significant associations are once again related to the main cutting edge of the blade – fine edges with no pattern produced a high frequency of defined margins than the patterned blades. Between scalloped and serrated blades there are variations in the frequencies of defined margins between the control and participant group. There are other factors that could affect the definition of the margins; the depth of the cut may be a factor - shallow kerfs could be more likely to give irregular margins for patterned blades as a result of the teeth travelling through the surface of the bone. Deeper kerfs may result in the kerf margins made or contacted by the flat part of the blade above the patterned edge which may result in a more defined edge.

The control group main channel was the location of a significant association between margin definition and the knife sub-class. At the vertebral margin, F1 and F3 had 100% defined margins, and F3 margins were split equally between defined and undefined. In the scalloped class, SC1 had the most frequent occurrence of defined kerfs (80%), whereas SC2 and SC3 had a higher proportion of undefined kerfs (63% and 84%). SR1 and SR2 both produced defined and undefined kerfs in approximately equal proportions, and in contrast, SR3 produced defined kerf margins more frequently (78%). The sternal margin showed the same trends for the fine blades as at the vertebral margin. SC1 kerf definition frequency increased to 100%, whilst SC2 and SC3 increased frequencies of defined kerfs when compared to the vertebral margins (87.5% for SC2, 50% for SC3). Serrated blades also showed an increase in the frequencies of defined kerf margins.

The lateral tips of the control group also demonstrated significant associations at the vertebral and sternal margins with knife sub-class. The vertebral margins had higher frequencies of defined kerfs for all of the fine knives than were recorded at the main channel. The scalloped blades followed the same trends as the main channel; SC1 with an increased frequency of defined kerfs, and SC2 and SC3 more likely to have undefined margins. SR1 produced greater frequencies of defined kerfs at the lateral tip than at the main channel; SR2 resulted in a greater number of undefined kerfs, and SR3 had an even split of frequencies for defined and undefined kerf classifications. The sternal margins at the lateral tip all produced higher frequencies of defined margins than the vertebral margin, with the exception of SR3.

There were differences in some of the relationships between knife types and the kerf when looking at the main channel and lateral tip. The definition or clarity of the edge of the kerf could be affected by differences in the bone surface at the different areas of the kerf, as well as the position of the knife as it moves through the bone; the contact between the blade and the bone surface may not be uniform throughout the kerf, with more contact in some areas than others, and therefore more or less definition in particular areas of the kerf; this may also vary according to the type of knife used.

The main channel and medial tip of the participant group are each the location of a significant association between the knife type and the margin definition for the vertebral margin (which for the participant group faces the flat back of the blade). The main channel had higher frequencies for regular margins across all blade types, with the exception of F2, which has equal numbers of kerfs with regular and irregular vertebral margins. The vertebral margin at the medial tip also has higher frequencies of regular margins, with the exceptions of SC2, with slightly more irregular than regular margins, and SR1, which has equal frequencies of irregular and regular margins. The lack of association with the sternal margin in the participant group is likely to be a combination of the patterned edge of the blades facing the sternal edge, creating a wider variation of blade/margin interactions as a result of individual differences in angle and force used by the participants. Surface differences in the bones across the group are another possible source of variation, as well as the location of the mark on the bone, which did vary more in the participant group than the control group. The rear of the blade, smooth and with a large flat surface area is common to all of the blades, and therefore may not a useful assessment criterion to identify knife blade type, even though significant associations are observable in both the control and the participant groups. It may be of interest to carry out work on blades with patterned edges on both sides of the blade to see whether any particular margin features are apparent, as margin definition may have potential use for broader classifications of blade type, e.g., single-patterned or double-patterned edges.

Another consideration is the response of margins to maceration methods; as they are at the surface of the bone, they may be more prone to damage and change as part of the tissue removal process.

The tip shape was also tested against margin definition; significant associations are found at the lateral tip for the control group, and the main channel for both control and participant groups. At the control group main channel, 83% of kerfs made by the blunt-tipped knife have undefined margins, compared to 32% of pointed blades with undefined margins. At the lateral tip of the control group, the trend at the vertebral margin is similar to the main channel; 83% undefined margins for the blunt blade and 37% of pointed kerfs have undefined margins. At the sternal margin for the participant group, all kerfs made by blunt blades (100%) had undefined margins. The pointed blades have more defined margins (56%) however the split between defined and undefined for pointed blades is more even in the participant group than the control group.

The participant group sample size is larger, but also will have a greater range of variation in the angle, direction and force of blade application which may account for the split of defined and undefined margins in pointed blades. Observing how and where the knife contacts the bone may also be useful as it is possible the blade tip does not always come into contact with the kerf. Margin definition may not be a useful feature for incised marks, but based on preliminary results it may be possible to apply margin definition as a diagnostic criterion for stab wounds to expand on the limited work done by Thompson and Inglis (2009).

The results all indicate that the kerf margin morphology can be linked to class features, particularly in distinguishing between patterned and fine blades, and that these trends hold even when different operators use the knives; however, the variation in frequencies between participant and control group may indicate that the angle and force, and the subsequent depth of the kerf may have an effect on the appearance of the margins. Previous studies such as Houck (1998) and Alunni-Perret *et al.* (2005) have used mechanical apparatus to examine marks with knife blades and Houck (1998) concludes that knife blades can be identified; however the current results illustrate that marks using the same knife made by a range of human operators show variation in kerf morphology, however overall trends between knife features and kerf features are still apparent. It is clear that the variables involved in making the marks need to be considered in further experiments; direct comparison of marks made by human operators and those made by mechanical means would be useful.

7.9 Margin splitting

Margin splitting was present in both control and participant groups but there were no significant associations between margin splitting for knife class, knife sub-class or tip shape. It is therefore considered to have no value in the classification of knife blade kerfs. Lewis (2008) discussed cracking in relation to distinguishing between sword and knife kerfs, as it is present in kerfs made by swords. The presence of splitting at the margins of the kerf for knife cuts indicates this is not a unique feature to swords; and therefore may not be used to distinguish between swords and knives as weapon classes. The size and degree of splitting could be examined as the splitting at knife kerf margins was visible microscopically; cracking made by swords may be easily visible macroscopically, unlike knife kerf splitting.

7.10 Lateral ridging

The control group has significant relationships between lateral ridging and blade class at the tips only; the vertebral medial tip and at vertebral and sternal margins for the lateral tip. At the medial tip lateral ridging occurred frequently in serrated blade kerfs (46.4%) in comparison to 22% of scalloped blade kerfs and 11% of fine blade kerfs. At the lateral tip, serrated blades also produced the most ridging at the vertebral margin (39%) compared to fine blade kerfs (21%) and scalloped blade kerfs (4%). At the sternal margin of the lateral tip, no serrated kerfs (0%) had lateral ridging, in comparison to 10% of fine blade kerfs and 22% of serrated blade kerfs.

The participant group has significant associations between lateral tip and blade class features at the sternal lateral tip and both margins at the main channel. At the lateral tip, fine blades rarely produce lateral ridging (9% of fine kerfs).

Scalloped blades produced more incidences of sternal lateral ridging in their kerfs (29%). At the main channel, sternal lateral ridging is least common in fine kerfs (25%) and most common in scalloped kerfs (55%). For the vertebral margins, fine blades produced more kerfs with lateral ridging (28%) in comparison to serrated (9%) and scalloped (6%).

The participant group had significant associations at the sternal and vertebral margins between lateral ridging and blade sub-class features. Lateral ridging at the main channel sternal margin (facing the patterned edge of the blade) was more frequently present than at the vertebral margins for all knife blade types. SC1 and SC3 both had high frequencies of lateral ridging when compared to other knife blade types. Alunni-Perret *et al.* (2005) suggested that this feature was a result of the knife entering the bone at an angle other than 90 degrees. Fine blades, as well as the patterned blades, have an increased frequency of lateral ridging at the sternal margin, negating the idea that the patterned edge is solely responsible for the increase. Most of the operators were right handed; when grasping the blade tightly in an overhand stab, clenching the knife in the right fist causes the orientation of the blade to tilt the spine toward the right, and the cutting edge to the left. If the knife was held in this position on application to the bone, the knife blade would be tilted, pushing down on the sternal walls and margins, causing the ridges at these margins. The author is right handed; and the control marks were made on left ribs, where the patterned part of the blade faces the vertebral plane. The trend described above is true for all blades with the exception of SC2 (one more occurrence than the vertebral margin), and SR1, which has lateral ridging equally at both margins. Further investigation may be necessary with a larger and more representative sample of left and right-handed operators to ascertain whether this feature could be potential indicator of handedness, which would be of interest to investigators.

7.11 Floor definition

Floor definition showed a significant association with the control group kerfs; fine blades produced defined floors in 81.5% of fine kerfs. In contrast, serrated and scalloped blades have a more even split of defined and undefined floors; 43% of scalloped kerf floors are defined, and 57% were undefined. Finally, 48% of serrated kerf floors showed definition, and 52% were undefined. No significant relationships were associated with the participant group. The floor definition demonstrated no association with the knife sub-class or knife tip shape for either kerf group examined. Symes (1992) and Symes *et al.* (2010) suggested that floor features are some of the most useful for the determination of class features when examining saw marks, however, the criterion of floor definition in its current form is of limited use for classification; although fine blade floors are more likely to be defined, the even split in patterned blade floors means that would not be reliable as a diagnostic indicator. This is compounded by the fact that a significant relationship does not exist for the participant group. The relationship between knife class and floor definition in the control group may indicate potential for the floor to have useful features for analysis; however, the criterion of floor definition is not specific enough. With reconsideration of observation features, there may be potential to establish the difference between patterned and fine blades. Any new criterion would also need to be significant in the participant group as well as the control group in order to be useful. Practically, it is also important to overcome some of the difficulties observing knife kerfs that are relatively narrow. The floor can also be obscured by other kerf features including projections or debris, and light microscopy does not always allow a clear view of the floor; lighting is important in the interpretation of the criteria, and lighting a small confined space is challenging. Digital optical microscopy or SEM analysis may provide opportunities for more detailed examination.

7.12 Floor width

The control group main channel demonstrated a significant relationship with floor width; 81.5% of fine blade kerfs are narrow, scalloped blades have an even split (50% each) narrow and wide, and serrated blades have 45.5% of serrated kerfs with narrow floors. There are no associations with the participant group which limits the potential use of this criterion in its current form. The results again indicate that there may be potential for identification between fine and patterned blade classes, and this may be better achieved by quantifying the criterion and measuring the kerf floor. Bartelink *et al.* (2001) stated that there was too much overlap between categories when kerfs were measured, however all of the knife blades were fine blades and the surface width was measured rather than the floor width. The marks were also made by a mechanical device. The current results indicate that manual operators also produce significant results for the same operator. Further work should involve the quantification of floor width to see if it has potential to distinguish between blade classes.

Floor width was the only floor feature to have a significant association with knife sub-class type. For the control group, this occurred at the main channel and lateral tip, and for the participant group, this occurred at the main channel and the medial tip.

The blade classes in the participant group gave a range of frequencies for floor value; narrow or wide floors were not restricted to any particular class, but the association may indicate that quantitative assessment of the floor width could be a useful potential indicator of the type of blade.

Although the participants had to stab from a fixed height and with a particular hand position, the angle and movement of the arm was uncontrolled and unrestricted. Differences in the way in which the knife is applied to bone may account for the different tip associations in the control and participant group.

Floor width and knife tip shape have a significant relationship for the participant group at the main channel; 80% of blunt blade kerfs had narrow floors compared to 44% for pointed blade kerfs. As the blunt sample set is small in comparison to the pointed blades, and the area of the knife blade that contacted the bone in each case is not known, the diagnostic use of this criterion in its current form is limited.

7.13 Floor splitting

Splitting of the kerf floor was a rare occurrence, and was not observed at all in the tips of the control group marks. No significant association with knife class, knife sub-class or knife tip shape was established. Floor splitting was therefore not a useful feature for the classification of knife blade kerfs.

7.14 Presence of debris in the kerf

Knife class and the presence of debris have a significant association for the control and the participant group at the medial tip.

For the control group, serrated blade kerfs have the highest incidence of debris (68%), followed by 61% of scalloped kerfs. In contrast, just 28% of fine blade kerfs contain debris. For the participant group, scalloped blade kerfs had the highest incidence of debris (85%) followed by serrated kerfs (74%). Fine blade kerfs have a much higher incidence of debris in the participant group (60%) than the control group.

Although serrated and scalloped kerfs have the greatest frequencies of debris presence and fine blades have the fewest, the relative amounts vary between control and participant groups highlighting where variation in force and angle of application may have an effect on the debris produced. The level of crossover between frequencies in both groups limits the use of this criterion for establishing class features.

Both control and participant groups exhibited a significant association between knife sub-class and the presence of debris within the kerf at the medial tip. Serrated and scalloped blade kerfs have higher frequencies of debris presence than fine blades for the participant group. Typically 80-90% of marks examined have debris present for SC1, SC2, SC3, SR1 and SR3. SR2 is the only exception, with debris presence occurring in 53.8% of kerfs. Fine blades range from 52%-72.7%. For the control group, SC1 and SR2 in particular showed high frequencies of debris presence; 80% of marks made by SC1 exhibited debris, and 90% of marks made by SC2. The fine blade group also exhibited lower incidences of debris presence than the participant group; 33.3% of F1 kerfs exhibited debris, no (0%) debris was observed in F3 kerf debris frequencies are more comparable with the participant group, at 57.1%.

In the participant group, the overall class trend for serrated and scalloped knives to produce debris in the cuts is more pronounced than the control group, for which only 2 knives show this tendency. In contrast, the absence of debris in fine-bladed kerfs is more distinct in the control group than the participant group at the medial tip.

The control group main channels also have a significant association between knife sub-class and debris presence. Like the relationship at the medial tip, some of the serrated and scalloped blades demonstrate high proportions of debris presence in their kerfs. SC1, SC3 and SR2 have debris in 100% of the kerfs examined. F1 and F2 both show much higher proportions of debris than at the medial tip (70%, and 78%, respectively). F2 follows the trend exhibited at the participant group medial tips for fine blades, with debris absent from 67% of kerfs examined.

The absence of any association with the lateral tip for class and sub-class features, and the strength of association at the medial tip with the presence of debris could be explained by the passage of the blade through the kerf. As the knife moves forwards and backwards through the bone, debris fragments are created, and may be pushed or pulled along with the blade; blade teeth may help this process as the recesses created by the teeth provide a mechanism for debris to travel through the kerf. The shape of the blade may also contribute, as the belly of the knife curves upwards towards the spine, meaning that the medial tip may not have as much contact with the straight part of the blade as the main channel or lateral tip. As the medial tip is the terminus of the downwards stroke, debris may accumulate in this area, pushed from the knife blade passage through the channel, and the raised belly means debris is not pulled back through the main channel. On excision (which is the lateral tip), the blade teeth along the flatter length of the blade pull back debris from the kerf, which may be lost as the knife blade is withdrawn.

Although a significant association between knife-class and debris presence is demonstrated at the main channel for the control group, this is not replicated in the participant experiment. Once possible explanation could be the wider variety of bones used in the participant experiment. Bromage and Boyde (1984) stated that the properties of individual bones influenced slicing mark morphology; this could result in some bones being more likely to produce debris than others. The other factors to take into account are the different operators and the variation of force and angle on application of the blade to bone, which may influence the creation of debris, as well as any movement in the kerf. The medial tip is also likely to be subject to less contact overall with the knife blade as the terminal part of the cut, whereas the main channel lateral tip could have the most contact with the dynamic action of the blade and therefore more susceptible to changes in angle and force.

Knife tip shape demonstrated a significant relationship with the lateral tip for the participant group only. All lateral tips of blunt tip kerfs contained debris compared to 63% of pointed kerfs. The small blunt sample needs to be expanded, however currently this criterion does not provide useful diagnostic criteria regarding tip shape of the blade.

7.15 Debris fragment type

Debris fragment type and knife class had no significant features at any part of the kerf for the control or participant group, however the type of debris fragment in the kerf was found to be a significant feature for subclass features at the main channel in both participant and control experiments, however the absence of a result for the Fisher's exact test combined with the absence of significant results at class level indicates a larger sample size needs to be tested to confirm a significant result. For the control experiment, serrated and scalloped blades as class groups showed no overall trend in terms of the type of fragment, but some knife types in each group were associated with different types of debris fragments. Flake fragments were observed in 60% of SC1 and 40% of SR2 kerfs; crushing fragments were observed in 50% of SC2 and 56% of SR1 kerfs. The participant group had lower frequencies of crushing for F1 kerfs (20%), and a higher frequency of crushing for F2 kerfs (57.1%). F3 kerfs had the highest frequency of flaking (41.7%) in the fine blade class. SC2 and SC3 have the highest frequencies of crushing (46.4% and 70%, respectively). Although some of the knives examined do show trends towards particular types of debris fragment, the only knife to feature similar frequencies and trends in both groups is SC2, with a higher incidence of crushing. SC2 has the lowest number of TPI, with less penetrating power. It also had the widest blade at both the spine and the cutting edge of the entire knife sample and a full tang, giving the knife a greater weight. The combination of these features may lend itself to the frequency of crushing seen in both the participant and control groups for the main channel.

The knife tip shape and debris type has a significant relationship at the main channel and lateral tip for the participant group only. At the lateral tip and main channel, blunt blade tips produced more kerfs with crushing debris (LT = 45.5%, MC = 63.6%) and pointed tips had more kerfs with no debris recorded (LT = 54%, MC = 36%). Although the blunt blade sample is small, the higher incidence of crushing may not be surprising given the thick unsharpened front of the blade. This criterion does not reliably distinguish between blunt and pointed blade tips.

7.16 Size of debris fragments

Class knife features and debris size have significant associations at the medial tip (control and participant group) and the main channel (control group only).At the control group medial tip; fine blades produce more kerfs with no debris (76%), and serrated blade kerfs have the greatest proportion of large fragments (27.6%). At the control main channel, scalloped and serrated blade kerfs have comparable levels of large fragments (36%); once again fine blades have no fragments in more of their kerfs (61%) and rarely produce large fragments (10%). Currently, the most useful aspect of this criterion result is the absence of debris in 61% of fine blade kerfs. Where debris is present, there is a degree of overlap between classes; future work could involve quantifying debris size to try and establish more discrete class boundaries.

In the knife sub-class main channel for a single operator, F1 and F3 had a high frequency of small fragments (60% and 70% of kerfs examined respectively). SR1 kerfs had mixed fragment sizes in 57% of kerfs, and 22% had large fragments only. SR2 kerfs also had mixed sizes (50%), with another 30% of kerfs containing large fragments only. SC1 kerfs contained the highest frequency of large fragments (70%), with another 10% of kerfs containing mixed debris sizes.

In the lateral tip, the trend for fine blades and small fragments was similar to the main channel; F1 and F2 both had only small fragments (60% and 11%), and there are no fragments present in F3 kerfs. SC1 had only large fragments (30%), and 40% of SR2 kerfs contain large fragments. There was a single occurrence of mixed debris sizes, for SR3.

The participant group showed no association with debris fragment size. This could be attributed to the range of ribs used from a number of individuals, fragmenting in different ways. It could also be a result of the variation in force applied to the bone by different operators, and the angle of application of the knife to the bone.

General trends such as the presence of small fragments in isolation in fine blade kerfs, and larger fragments or mixed fragments were present in the scalloped and serrated class appears to have potential for classification purposes, there is overlap. In addition, there would also be difficulty in overcoming potential limitations such as recreating the circumstances of the original mark for comparison, including the force and angle used to make the original mark, and considering the potential for the bone itself to vary the appearance of the kerf.

The knife tip shape has significant associations at the participant lateral tip only. Blunt blades have higher proportions of small fragments (45.5%) in their kerfs compared to pointed blades (14%). The sample size for the blunt blade is smaller than the pointed blades, and needs to be expanded in order to clarify the extent of the result significance. At this stage, the criterion cannot be used to distinguish between pointed and blunt blades reliably.

7.17 Type of debris material

Tennick *et al.* (2008) showed metal fragments in the kerf, as well as bone and tissue debris. Considering the potential for trace analysis from metal fragments recovered from the kerf, the type of debris material was recorded. The debris material showed a significant relationship with the knife class at the medial tip of the control and the participant group, and the main channel of the control group. The main channel in the control group showed a significant association between debris material and knife subclass. A single metal fragment was observed in this study, for a scalloped blade in the medial tip, therefore eliminating any real potential for trace analysis from metal debris as it is a rare occurrence. The debris material consisted of bone and other residues. Residual tissue in the kerf was problematic when making morphological assessments, and there were a number of kerfs for which the floor or walls could not be seen as a result of remaining residue after the maceration process. Bones were not macerated again in order to prevent further damage to the kerf. The bones were left to dry in an upright position; a suggested modification to this technique in the future would be to invert the bones on a stand, preventing the kerf from damage as a result of being wetted and laid on a flat surface, but allowing full drainage of residual liquids from the kerfs.

7.18 Summary

This thesis gathered and clarified existing mark criteria, and created new mark criteria in order to create the most comprehensive and extensive analysis of cut mark features with the largest sample of knife blades and different blade classes. It is also the first knife blade study to use a range of human operators to make knife cuts exclusively. The use of mechanical apparatus in the application of weapons to bone is common practice (Houck, 1998; Bartelink *et al*., 2001; Alunni-Perret *et al*., 2005, Shaw *et al.*, 2011), however work examining human force and comparing it to drop-tower testing indicated that the two motions are not comparable (Chadwick *et al.* 1999). Although results suggest that trends do exist between class features of knife blades and kerf morphology in a number of areas, the variation within the results (both within the participant group and between the participant group and the control group) indicated that human operators can produce morphologically different marks (when comparing one specific feature) with the same knife blade under similar conditions. This is important as any future studies testing aspects of trauma using mechanical means need to consider that the results may not be reproduced to the same degree using human operators.

The data also challenge established knowledge in the field, particularly concerning cross-section shape and tip features. Symes *et al.* (2010) suggest that serrated blades produce narrow v-shaped profiles, others also suggest knives produce V-shaped kerfs (Greenfield, 1999; Alunni-Perret *et al.* 2005, Lewis, 2008) however present data indicates that this is not always the case; the differentiation between serrated and scalloped blades classes for the first time shows that there can be more variety in the overall kerf shape, particularly for scalloped blades. Tips of the kerf were examined separately; Symes *et al.* (2010) suggest that flaring at the tip indicated the blade handle position. All work on tip features indicates that no feature is unique to either tip and therefore this feature cannot be established as useful in knife blades.

Although none of the features examined are definitively unique to any particular knife class or sub-class, the presence of trends in both groups on the basis of broad criteria for examination is encouraging, indicating the potential for further analysis with re-evaluation of criteria and possibly the examination of more specific features within each criterion. Quantification of features such as floor width or projection size may provide more discrimination than the broad categories examined to date.

In summation, none of the features examined above have been able to definitively distinguish between class features of knives. More significant associations are present in the control group than the participant groups; few features exhibit similar trends in both. Some variables discussed such as wall gradient, or margin definition and regularity, show links to features of the knives, but they tend to be class features without power to discriminate one knife from another. The number of features with significant associations for the knife blade, and the subsequent decrease in these features for the group with numerous operators highlights the effect that individuals can have on the mark made, obliterating features present with a single operator. Although there is potential for the marks to be operator influenced, some trends, such as lateral ridging, or wall slope still show similar trends when marks are made by different people under similar conditions. The similar conditions themselves are restricted to the bone and knife at the same height for stabbing, and a consistent grip on the weapon. The force and angle were uncontrolled, although participants were instructed to make marks of a similar force. The force graphs indicate that participant forces vary (see appendix); this could be a contributing factor to differences observed. The location and number of marks found after maceration also varied between individuals, and so analysis of traits in relation to the force could not be carried out, as the force peaks could not be reliably attributed to a kerf. Previous studies such as Humphrey and Hutchinson, (2001) and Tucker *et al*. (2001), control for force as a variable by declaring that the same operator was used, and the force was gauged to be the same (though unmeasured). The force graphs indicate that perception of equal force may not be reliable, and no studies exist that examine the relationship between different forces and incision marks on bone. The variation introduced by individual operators also calls into question the practice of using guillotine devices and other apparatus to strictly control force and angle, as the practical applications of mark observations made in this way are likely to be unrealistic in their level of similarity. There is potential for more work around the mechanics of stabbing in bone; developments might include filming participants as they make the marks, and monitoring the position of the knife blade as it travels through bone or tissue to make each kerf may also be useful.

The interaction of the blade and bone surface, such as the difference between a stabbing action and an incised or sawing action should be considered when analysing marks. Incised wounds were examined, and the depth of marks varied. Variation in results also highlights the potential complexities of incised marks made by human operators rather than marks made with a single dropped motion. Variation in depth is an issue that may affect the morphology of mark features which may not be encountered in force-controlled studies or drop-tower tests.

On examination of the blade profiles, the depth of the cut would have an impact on any potential features to be transferred to bone as contrasting areas of interest may not make contact in very shallow cuts. The serrated and scalloped blades used in the present research each have different tooth heights; the points of the tooth may interact with the bone surface, but if the mark is very shallow, variable contact with the tooth blade in-between the points will occur, depending on the depth of the cut.

Bevels in the fine–edged blades could potentially leave more detail in a deeper cut than a shallow one; the variation in angle and height of the bevels for each blade may not be reflected in marks made of the same shallow depth, depending on the knife features. The knives, though comparable in size and type, do have slight variations in the angle or taper of the blade from the handle to the tip; expanding the study to look at stab wounds (punctures) as well as the incised kerfs might have the potential to be useful as there seemed to be variation at the tip of the blades that may transfer to a puncture mark, but the depth, once again, would be an important factor. Although participants decided their own level of force, the forces used in the study are still controlled as participants concentrated on trying to make marks on a small target; giving participants a greater surface area to work with (such as an articulated series of ribs) might encourage forces more representative of those used in knife crime.

In trying to keep blades a comparable size, it was difficult to source utility-style scalloped blades; as one of the blades has a rounded edge, analysis of the pointed tips against the round trip was carried out; more in-depth analysis is required as the rounded blade sample is relatively small; however the results indicate that relatively few parts of the kerf may be affected by the rounded edge; margin regularity and definition, as well as the size and amount of debris found in the cut.

For very shallow marks, it is possible that useful features may be less prevalent, as variations in bevel depth for fine-edged blades, and the height of the tooth arc in serrated and scalloped blades

Although the use of a single human control was novel, it would have been useful to have additional machine-made marks for comparison. If using human operators for control comparison again, it would be valuable to double or triple the amount of marks required, in order that the number of marks that land on bone is enough for a detailed and thorough analysis. Taking several operators, and having a number of human controls with repeats using the same knife blade may also have strengthened the data; as well as making marks on bone in the first place, the ability to observe features has a big impact on the potential for statistical analysis; more marks should results in more opportunities for observable data to be gathered from the samples. By comparing the human data with machine data, we could also establish the limitations of machine and man-made marks for laboratory experiments, and inform future practice.

It is proposed that there is still a great deal to understand about the dynamics of cut marks and their identification; what the results do show is that even with simple, broad categories, knife cuts in bone indicate trends that could be used to narrow down potential weapon sources, and have highlighted potential areas for further and more in-depth examination. The individualisation of marks on bone may be a target for the future, but it is clear that classification may be the next step, building on the trends identified in this thesis.

Chapter 8 Conclusion

This thesis examined an extensive series of kerf features, redefining existing criteria and proposing novel features for analysis. A range of kerf and knife blade characteristics have been examined using optical microscopy. Kerf marks were split into three sections; the main channel, and medial and lateral tips, and each part of the kerf was examined and scored separately. The results indicated that the main channel contained the most significant associations between kerf characteristics and blade type; tips contained fewer significant associations and overall had similar trends to the main channel. There is therefore no clear advantage to examining and classifying the tips separately using optical microscopy.

Many of the features put forward for kerf classification did not have any significant association with the knives, including tip shape, margin splitting and floor splitting.

Previous studies (Symes, 1992) have suggested that the kerf floor is the most useful feature in the kerf, but this was not the case with the kerf sample sets. A number of factors that either prevented or hampered floor examination included the presence of debris in the kerf, large wall projections obscuring the floor, depth of the kerf, or difficulties with adequately lighting and viewing the floor using a conventional low-power stereomicroscope.

There were other kerf features that showed significant associations with knife features, but the nature of the relationship was not useful as a classification criterion to identify knife type, these include tip shape, bifurcation, cross-sectional shape, wall projection size and frequency, and the presence size and type of debris found in the kerf.

Some of the results challenge established data, such as the V - cross-section shape for patterned blades and the broader range of shapes examined, in addition to the presence of tip features used to determine handle directionality

(Symes *et al.* 2010); this classification feature is not present in knives, although patterned blades have been compared to saws (Symes, 1992; Symes *et al.* 2010)

Several other parts of the kerf structure have shown significant associations with knife features, and have clearer relationships with blade features including the walls, margins and floor; in particular, the wall gradient, margin regularity and definition, lateral ridging, and floor width. Wall gradient has a relationship with the slope of the blade, and has potential for further investigation. Margin regularity highlights different relationships with the cutting edge and the rear of the blade, and margin definition also has a relationship with the back of the blade, indicating that the margins of the kerf may warrant further investigation; lateral ridging does not help in the classification of the blade, however it may provide information about the angle of the blade which could be used as intelligence information to establish handedness. Floor width has a significant association in both the control and the participant groups, with each blade exhibiting different frequencies of wide and narrow margin. Quantification of the floor width could have classification potential.

Although optical microscopy was not successful in providing discrete classification criteria for blade types from the knife samples examined, it did identify relationships between the blade and the kerf which could be refined further. The current research indicates that it is possible to establish trends between knife blades of a similar class, using human subjects to make the cut marks. Conversely, trends identified in the control kerfs made by a single individual, did not always apply when the same knives were used by a range of operators. This indicates that the circumstances in which the cut mark is made are important, highlighting the need to understand more about the nature of kerfs, and how human influence affects the kerfs made. Work that involves mechanical apparatus to control force and angle may therefore produce marks with artificial levels of similarity, which has limited value in practical application to real cases.

The results indicate that potential still exists for reliable classification of knife blades based on mark morphology.

This thesis:

- Categorised utility knives by identifying potential characteristics that may influence marks made in a surface medium.

- Identified features within a knife cut on bone that can be examined microscopically, and classification criteria were designed to be used for assessment.

- Demonstrated that statistical testing has been applied to confirm which kerf features can be associated with features of the knife blade.

- Tested individuals when using knives to make marks on bone, and compared marks made by a range of individuals to marks made by a single individual. The feasibility of the wider application of criteria has been discussed.

- Investigated knife cut features to create a criteria-based assessment system to diagnose potential weapons from unknown marks; the criteria were able to identify trends, but further work is needed to accurately identify knife blade class from kerf features.

8.1 Further Work

Optical microscopy has provided a useful starting point for the identification of kerf features with potential for identification. The digital optical microscope may be a good intermediary between optical light microscopy and SEM. Software allows layer-by-layer scanning of material, so there are no depth of field problems, and the scanning process allows electronic 3D models to be produced of the kerf, allowing more accurate classification of features traditionally difficult to observe using optical light microscopy, such as the cross-section profile, floors and wall features. The microscopes also permit features to be more accurately measured than conventional light microscopy, meaning features such as the width of the kerf floor could be quantified; angles can also be measured so the quantification of wall gradient may also be possible. Quantification of the floor width may be useful for classification as it has close contact with cutting edge which varied between the blade classes. The scanning process can also provide an opportunity to observe more subtle changes in morphology in the walls, floor and margins. Quantification and comparison of the wall gradients may be useful to give an indication of blade shape, such as the presence or absence of bevels. Refinements to the margin criteria may be important to establish the level to which they reflect the patterned and unpatterned edges of the blade, building on the trends identified by this thesis. Quantification of wall projection size may also be useful for classification, in addition to refining criteria around the shape of wall projections and comparing them directly with patterned blade features.

The depth of the kerf is another important variable which needs further consideration. Comparisons of blade criteria made by marks at fixed depths may be valuable to establish the extent to which kerf features change with depth.

This thesis separated serrated and scalloped blades and compared them for the first time. Scalloped blades in particular are not referred to in any other publication. Patterned blades need to be examined in more depth, so the knife sample set could be expanded to examine other classes to see whether trends continue or vary depending on the knife type (e.g., carving) and size.

When using human operators, it may be useful to compare marks made by left and right handed operators; there were a limited number of left-handed operators available for the thesis data. This may also help to clarify the significance or usefulness of lateral ridging in indicating handedness.

Mark force is a variable which needs further investigation; the variation in the application of force and its effect on mark appearance and identification has not been addressed in the research to date, and to assess the potential use of any identification techniques for toolmarks on bone, the scope and breadth of variation should be explored in more depth. Although the use of human operators is novel for the context of this project, the forces are still controlled; and participants, in concentrating on hitting the bone, are not applying as much force as may be used in more frenzied attacks. Examining the differences between low impact marks and those made by high impact attacks at speed may also be useful for the forensic examiner, particularly if the marks vary as a result of the variation of speed and force in the attack. Studies to date such as Walker and Long (1977), Bello and Soligo (2008), and Boschin and Crezzini (2011) have focussed on fine-edged blades; this thesis has examined patterned knife blades in more detail than other work (such as Thompson and Inglis, (2009) or Symes (1998); however, the potential to distinguish between different types of patterned knife blades could be further explored, as class features identified from patterned blades could be extremely useful for a forensic examiner. This thesis has touched upon the shape of the knife tip and exploring the effect that may have on marks made in bone; however the range and morphology of kitchen blades and other knife types also needs to be examined in more depth, as the blade shape has the potential to affect the blade interaction with bone and therefore the quality and appearance of any cut marks that may occur. Stab wounds in bone could be examined, building on the limited work of Thompson and Inglis (2009). Separate criteria could be proposed and tested to establish the extent to which knife blade can be classified from punctures as a result of stabbing in bone.

Houck (1998) and Alunni-Perret *et. al.* (2005) used mechanical apparatus to apply their weapons to bone; a further study would be to compare the data from marks made by human operators with marks made by the same knives using mechanical apparatus in order to adequately measure the variation in the types of marks that are produced by these processes, and how readily comparable the marks produced are to one another.

This thesis involved macerating bones to examine marks; it would also be valuable to examine marks made on fresh bone, and possibly compare these with marks made through flesh that need to undergo the maceration process, or marks in decaying remains. Monitoring the morphology of marks through processes either used in enhancing the marks for observation, or simply by allowing marks to undergo the decomposition process to see the level of effect would also have potential implications for the forensic examiner.

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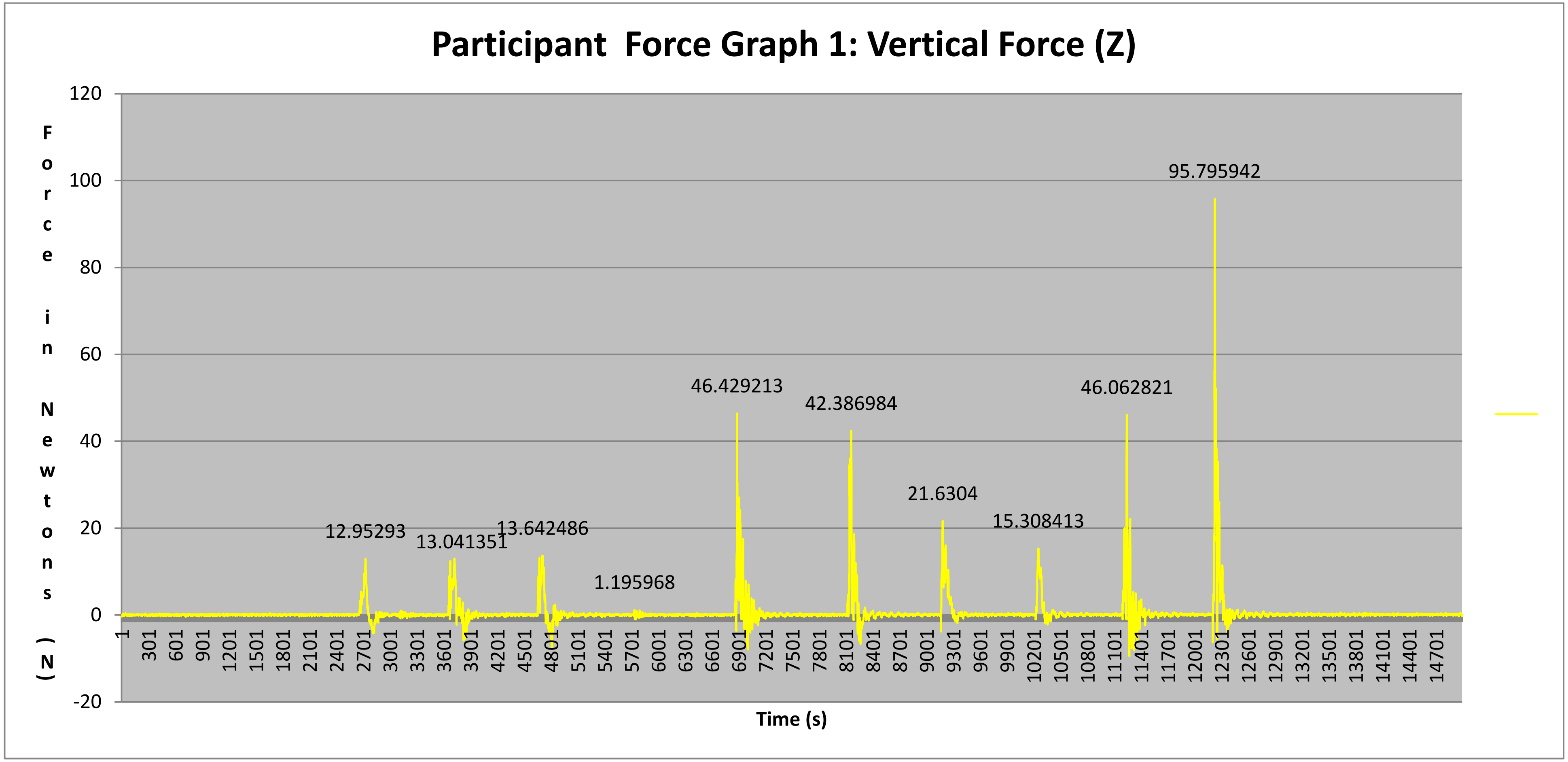
Appendices

The classification proforma used when assessing each mark, used for classification of the medial and lateral tips.

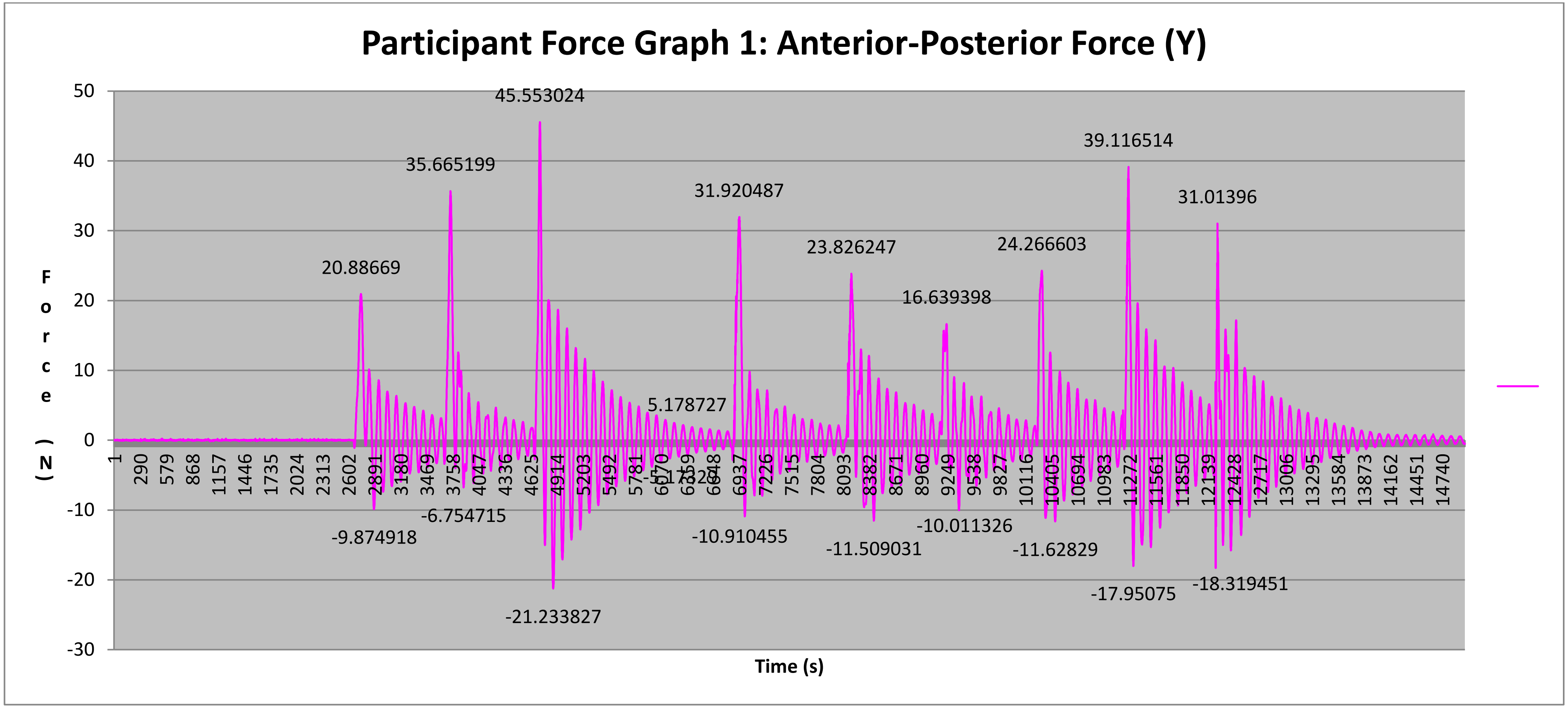
General Mark characteristics			**Mark No:**	**……………..**	**Knife No:**	**……………**	
Max width	………………		*Min width*	………………			
Associated marks?	Y/N		*Bone surface*	Superior	Inferior		
Medial Tip							
Shape	Rounded	Square	Tapered	Unobservable	Other		
Bifurcation	Y/N						
X-Section shape	V	U	Unobservable	Other			
Wall gradient (Vertebral)	Very steep	Steep	None	Shallow	Very Shallow		
Wall gradient (Sternal)	Very steep	Steep	None	Shallow	Very Shallow		
Wall projections	Many	Few	None	Large	Small		
Margins (Vertebral)	Regular	Irregular	Defined	Undefined	Splitting		
Margins (Sternal)	Regular	Irregular	Defined	Undefined	Splitting		
Floor	Defined	Undefined	Wide	Narrow	Splitting	Debris	
Debris	Absent	Crushing	Flaking	Large	Fine	Type?	
Lateral ridging	Y/N	Vertebral	Sternal	Both			
Surrounding bone surface	Porous	Non-porous	Smooth	Textured	Steep gradient	Little gradient	No gradient
Lateral Tip							
Shape	Rounded	Square	Tapered	Unobservable	Other		
Bifurcation	Y/N						
X-Section shape	V	U	Unobservable	Other			
Wall gradient (Vertebral)	Very steep	Steep	None	Shallow	Very Shallow		
Wall gradient (Sternal)	Very steep	Steep	None	Shallow	Very Shallow		
Wall projections	Many	Few	None	Large	Small		
Margins (Vertebral)	Regular	Irregular	Defined	Undefined	Splitting		
Margins (Sternal)	Regular	Irregular	Defined	Undefined	Splitting		
Floor	Defined	Undefined	Wide	Narrow	Splitting	Debris	
Debris	Absent	Crushing	Flaking	Large	Fine	Type?	
Lateral ridging	Y/N	Vertebral	Sternal	Both			
Surrounding bone surface	Porous	Non-porous	Smooth	Textured	Steep gradient	Little gradient	No gradient

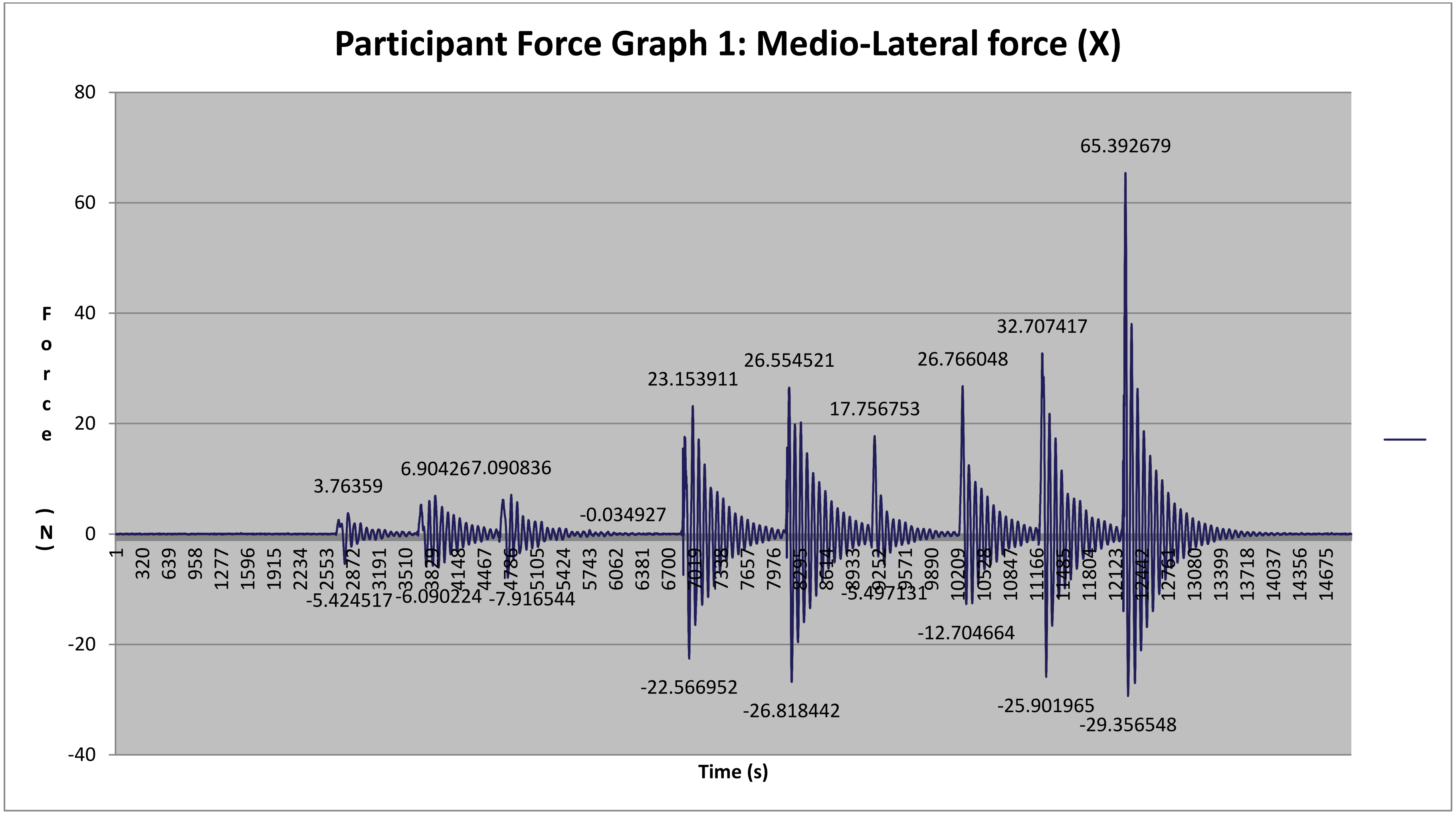
The classification proforma used when assessing each mark, used for classification of the main channel.

General Mark characteristics			**Mark No:**	……………….	**Knife No:**	……………….	
Max width	……………….		*Min width*	……………….			
Associated marks?	Y/N		*Bone surface*	Superior	Inferior		
Main Channel							
Width	Wide	Narrow	Consistent	Varied			
Depth	Shallow	Deep	Consistent		Varied		
X-Section shape	V	U	Unobservable	Other			
Wall gradient (Vertebral)	Very steep	Steep	None	Shallow	Very Shallow		
Wall gradient (Sternal)	Very steep	Steep	None	Shallow	Very Shallow		
Wall projections	Many	Few	None	Large	Small		
Margins (Vertebral)	Regular	Irregular	Defined	Undefined	Splitting		
Margins (Sternal)	Regular	Irregular	Defined	Undefined	Splitting		
Floor	Defined	Undefined	Wide	Narrow	Splitting	Debris	
Debris	Absent	Crushing	Flaking	Large	Fine	Type?	
Lateral ridging	Y/N	Vertebral	Sternal	Both			
Surrounding bone surface	Porous	Non-porous	Smooth	Textured	Steep gradient	Little gradient	No gradient

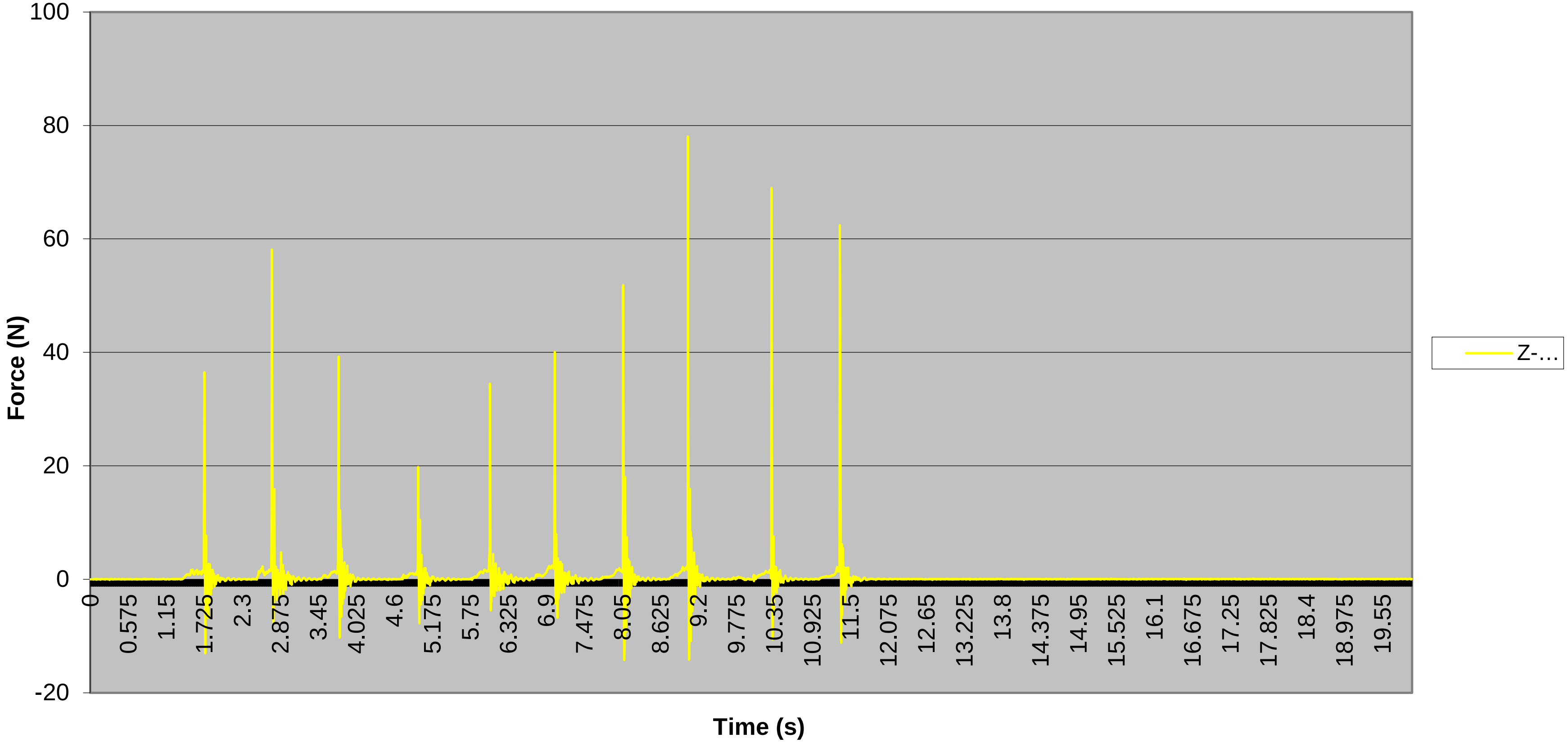


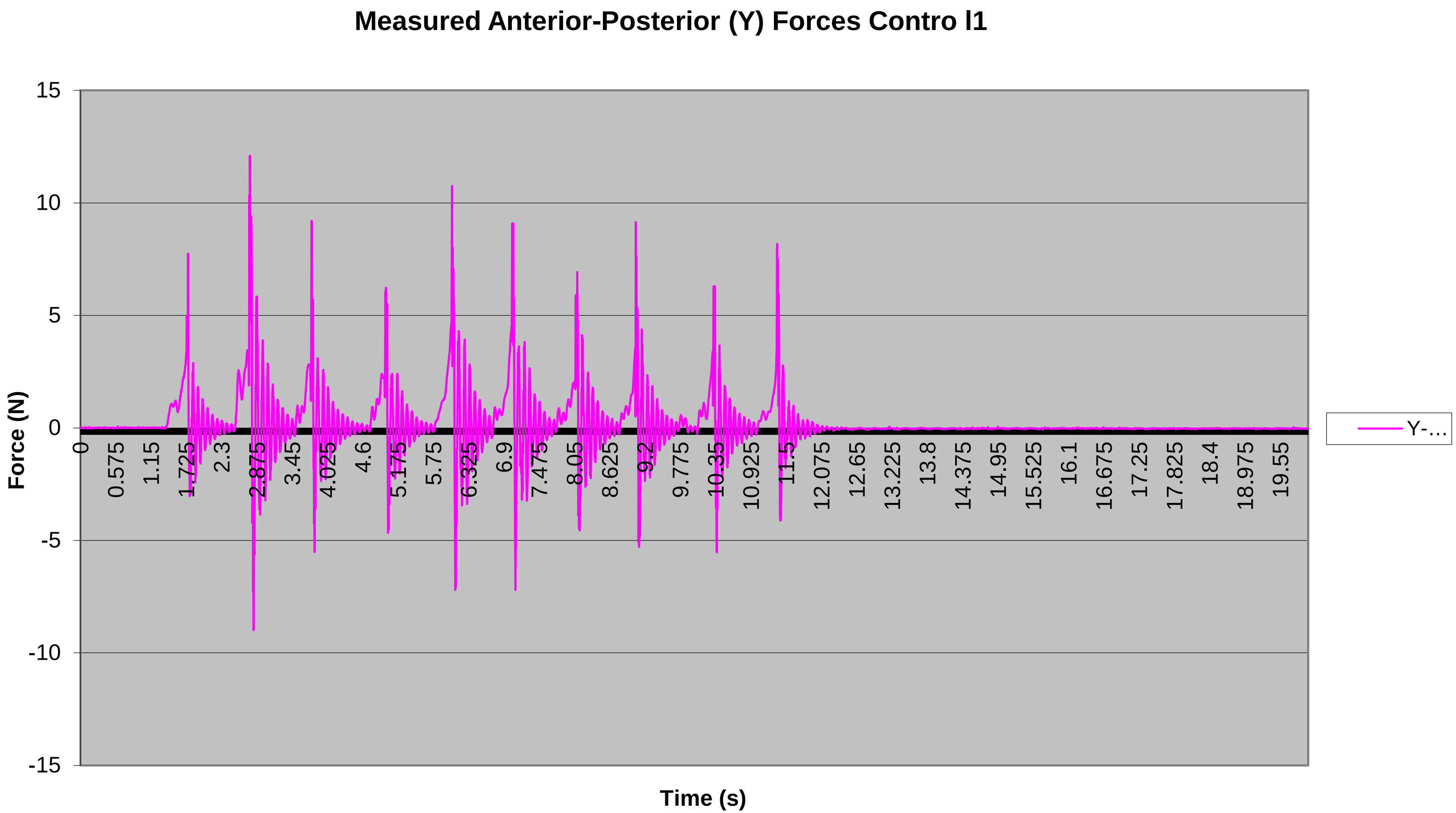
Participant Force Graph 1: Vertical Force (Z)
Force in Newtons (N)
Time (s)
120
100
80
60
40
20
0
-20
12.95293
13.041351
13.642486
1.195968
46.429213
42.386984
21.6304
15.308413
46.062821
95.795942


Participant Force Graph 1: Anterior-Posterior Force (Y)
Force (N)
Time (s)
45.553024
35.665199
20.88669
31.920487
23.826247
16.639398
24.266603
39.116514
31.01396
5.178727
-9.874918
-6.754715
-21.233827
-10.910455
-11.509031
-10.011326
-11.62829
-17.95075
-18.319451


Participant Force Graph 1: Medio-Lateral force (X)
Force (N)
Time (s)
80
60
40
20
0
-20
-40
65.392679
32.707417
26.554521
26.766048
23.153911
17.756753
6.904267.090836
3.76359
-0.034927
-5.424517
-6.090224
-7.916544
-5.497131
-12.704664
-22.566952
-26.818442
-25.901965
-29.356548

Measured Vertical (Z) Forces Control 1




Measured Anterior-Posterior (Y) Forces Contro l1
Force (N)
15
10
5
0
-5
-10
-15
0
0.575
1.15
1.725
2.3
2.875
3.45
4.025
4.6
5.175
5.75
6.325
6.9
7.475
8.05
8.625
9.2
9.775
10.35
10.925
11.5
12.075
12.65
13.225
13.8
14.375
14.95
15.525
16.1
16.675
17.25
17.825
18.4
18.975
19.55
Time (s)
Y-...

Measured Medio-Lateral (X) Forces Control 1