



# The Influence of Fabric Resistance on Experimental Applications of Skeletal Trauma: An Analysis of Sharp Force Trauma by Serrated Knives

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## Abstract

Despite the abundance of validation studies in sharp force trauma literature, there is a lack of research that examines the effects of fabric resistance during stabbing events. In this study, experimental knife trauma via a guided-drop impacting device was used to identify toolmark characteristics on clothed and unclothed skeletal remains. Five clothing fabrics [drill, satin, cotton, polyester, and cotton comforter] and two knives [serrated and scalloped] were used to create 180 cut marks on porcine ribs. Kerf marks were macerated in a detergent solution and measured by scoring kerfs using kerf characteristic measurements. Multivariate tests indicated that clothed specimens produced decreased striations and wall projections, kerf width, kerf depth, and altered kerf shape [ $p < 0.05$ ]. This study found that fabric variables altered kerf characteristics and produced distinguishable marks on unclothed and clothed remains. Results revealed that scalloped knives more often produced U-shaped cross-sections as a result of blade skipping and blade snagging on fabric. Standard light microscopy was found to be an effective method for examining characteristics not visible macroscopically.

**Keywords:** Forensic anthropology; Forensic science; Sharp force trauma; Osteological trauma; Cut mark analysis; Criminalistics

## Introduction

Sharp force trauma is a prevalent form of homicide and injury in the United States and the United Kingdom. Analyses of sharp force injuries in forensic literature have been consistently documented; however, there is still a dearth of studies that link weapons to skeletal injuries. Despite the fact that in a significant number of homicide cases, victims are clothed, little data exist on the effects of fabric resistance and flesh on injuries during stabbing events [1]. Understanding the effects of fabric resistance on sharp force injuries is critical for accurate identification of toolmark characteristics. According to statistics released by the National Crime Victim's Survey, crimes involving knives or other sharp objects accounted for 25% of annual crimes between 1993 and 2001 in the United States [2]. Data collected from the FBI's Homicide Report in 2011 indicated that women are far more likely to be killed at home than in any other locale, and knives and other cutting instruments accounted for 20 percent of all female murders [3]. The study also reports that domestic violence-related homicides occurred frequently with 94 per cent of the female victims [1,509 out of 1,601] being murdered by a male they knew [3]. Stabbing incidents occur in a variety of locations and circumstances; yet, the access to a knife or other cutting instrument is likely to have come from the home, as knives have the advantage of being easily obtained and concealed [4]. Due to the prevalence of knife crime, sharp force trauma analysis is an area of much needed research.

Skeletal trauma is created by the application of energy on a continuum from high to low levels of input on the human body and is classified as sharp force or blunt force depending on factors such as directionality, velocity, and focus of impact [5-8]. Sharp force trauma occurs when force is applied over a narrow focus of impact using a sharp-edged tool or instrument [6]. According to Thompson and Inglis, characteristics of marks that are indicative of weapon type involve the classification of kerf features, wall characteristics, margin characteristics, floor characteristics, and debris characteristics that also depend on blade edge type, anatomy, and class characteristics of blade types [9]. This research suggests that a weapon with two cutting edges tends to produce a wound with sharp edges and clean cuts, and

single-edged blades are likely to cause splitting or fishtailing at one end as a result of the blunt back of the weapon. When considering the properties of cortical bone, certain characteristics are more prevalent when examining marks on bone compared to incised wounds. For instance, cut mark shape on bone tends to become more rounded when the weapon is withdrawn due to skin elasticity [10]. Furthermore, knife marks are usually narrower than the width because lesions on fresh cortical bone usually close following weapon withdrawal due to the elastic nature of bone [11]. Nonetheless, the effects of fabric resistance on splitting, fishtailing, and rounding in kerf marks have not been consistently documented [11]. Although fabric analyses often assist in investigation surrounding the circumstances of death, fabric has seldom been analyzed in comparison to marks and stab wounds found on skin and bone. Furthermore, the structural stabilization and degradation of fabric altered through laundering has not been highly investigated [12]. Sharp force trauma injuries are often accompanied by cutting damage to clothing, therefore, corroborating research can be very useful in linking weapons through the identification of consistent characteristics and features.

Additionally, accurate documentation and reporting is crucial to forensic investigation. Discrepancies in standards, misleading information, and improper reporting of data can result in substantial misinterpretations by law enforcement, judges, attorneys, and juries [9,13]. For instance, forensic students are often taught that certain characteristics, such as a U-shaped kerf cross-section, would exclude serrated and nonserrated knives as potential weapons [13].

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Furthermore, the use of descriptors such as “sharp,” “single-edged blade,” and “hesitation mark” [which inaccurately emphasizes behavior], can result in serious misinterpretations by law enforcement officers, judges, attorneys, and juries. These discrepancies call into question the accuracy of current trauma analyses methods and validation standards. By including fabric resistance variables in this study, a more holistic view may be provided to forensic scientists and investigators. The current body of literature on sharp force trauma skeletal wounds frequently excludes fabric variables, and this is not representative of actual forensic scenarios [4,10,12,14,15]. Furthermore, due to the prevalence of fatal homicides in domestic violence disputes occurring in the bedroom, an analysis of bedding fabric along with common clothing fabrics may provide useful forensic information which may better aid in homicide investigations and postmortem interval determination [16]. The purpose of this experimental study was to examine the implications of fabric resistance in relation to sharp force trauma wounds on skeletal remains.

## Materials and Methods

Five fabric materials and two serrated instruments were obtained from Ross Dress For Less®. The clothing specimens used in the study included: (1) cotton, (2) polyester, (3) jean drill, (4) cotton comforter (100% polyester/cotton blend), and (5) satin (100% polyester/satin blend). Prior to the experimental study, fabrics were laundered, as forensic studies on fabric have indicated that degradation of the integrity of the fibers due to laundering impacts stabbing resistance [12]. Two serrated knives, including (a) a standard serrated knife and (b) a scalloped knife, were purchased and used prior to the experimental study. This allowed for the examination of wear and imperfections on the blade that more closely resemble actual forensic scenarios. Since existing research indicates that kitchen knives are most commonly used in homicides, used kitchen knives were utilized during the study.

The sample was obtained from six domestic porcine carcasses purchased from Willow Glen Meats and Smokehouse. The porcine samples were examined for any marks prior to guided drop impact tests. Porcine remains were used as they are often used as a suitable medium to replicate trauma on human remains. Because remains were declared fit for consumption, the overall sample was fairly homogenous in terms of factors, such as illness and disease, due to industry standards. The chest cavity is most likely to be impacted during homicides and stabbing injuries, so ribs were chosen to more closely resemble real-life scenarios. Though postmortem sharp force trauma differs from trauma observed on live individuals, these analyses can be applied to postmortem dismemberment cases.

## Scoring measurements

Characteristics of blades and kerf marks were examined and scored based on pre-selected criteria from previous studies. Kerf mark characteristics include measurements on cross-section, depth, width, length, striations, wall projections, wall gradient, margins, floor, debris, and lateral ridging [17-24]. The kerf characteristics included in this study include: striations and wall projections, kerf width, kerf depth, and kerf shape. Qualitative scores were used to assess kerf width, kerf depth, and kerf shape because digital calipers could not give accurate readings for these features.

Striations are defined as linear marks that occur from cutting action. Regular striations are observed at regular intervals, while intervals of irregular striations are variable. Striations are considered a diagnostic characteristic of serrated blades and are observable on cut

marks. Wall projections are defined as breakaway spurs of bone that occur through sharp force trauma. Striations were scored as present or absent, and wall projects were scored based on the number of bony projections present in the kerf.

Kerf width is defined as a horizontal measurement of the two furthest points on the kerf. Width was scored as: (1) wide, if the width was greater than 25% of the kerf height, (2) narrow, if the width was narrower than 25% of the kerf height, (3) consistent, if it kerf width and height were uniform and it was difficult to classify whether width as greater or narrower than 25% of the height, and (4) varied, if the width was difficult to measure due to a lack of uniformity.

Kerf depth refers to the measurement from the kerf edge to the deepest point of the kerf floor. Depth was scored as: (1) shallow, if the depth was less than 25% of the kerf height, (2) deep, if the depth was greater than 25% of the kerf height, (3) consistent, if the kerf depth and kerf height were uniform and it was difficult to classify whether the depth was greater or narrower than 25% of the height, and (4) varied, if the depth was inconsistent.

Kerf shape included measurements from cross-sections and wall gradients, due to the strong correlation in the data. The cross-section refers to the profile shape of the kerf walls (Figure 1). Cross-section was scored as: (1) V-shaped, if the walls came to a point [the walls meet at one point, creating a V-shape], (2) U-shaped, if the walls did not come to a point [the walls do not meet at a single point, creating a U-shape], (3) unobservable, if the cross-section was not able to be identified, and (4) other, if the cross-section differed from a V or U shape. Cross-sections that did not have a V or U shape exhibited undefined margins or significant distortion by debris. Wall gradients are defined as the angle of kerf walls in relation to the kerf floor. Wall gradients were scored as: (1) very steep, if the walls were at a 90° angle, (2) steep, if the walls were between a 45° and 90° angle, (3) none, if no walls were present, (4) shallow, if the walls were less than a 45° angle, and (5) very shallow, if walls were present but close to a 0° angle (Figure 1).

## Impact tests

A guided-drop impacting device was used to control force of impact and minimize error by creating cut marks as consistently as possible. Each specimen was placed onto a flat wooden block secured on to a

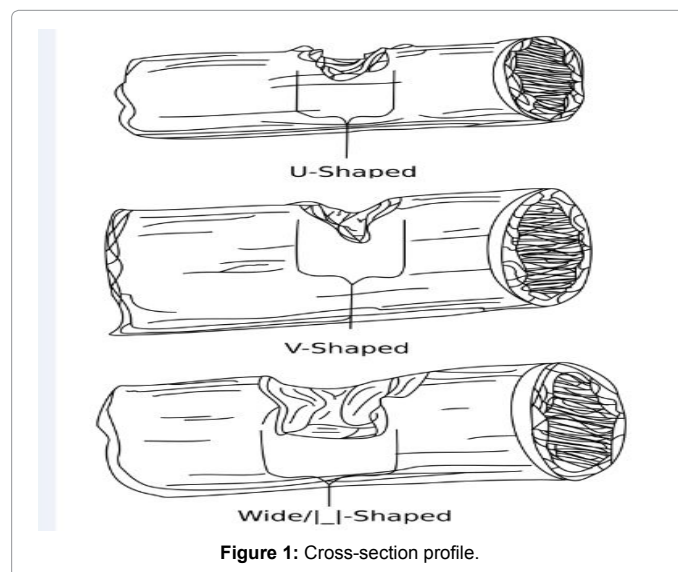


Figure 1: Cross-section profile.

NEULOG 225 force plate sensor. Weapon blades were attached to a 1” x 10” metal pipe that impacted the specimen by guided free fall through a 1.5” wide PVC pipe placed over the specimen. To attach the weapon blades, the 1” x 10” metal pipes were filled with RapidSet® cement, the weapons were placed inside the metal pipes, and the impact blades cured for approximately two hours. The weapon was placed within the pipe to ensure that the length of the protruding blade tip was consistent in all of the impact blades. Dimension measurements, including the weight, length of instrument, width of instrument, blade length, blade width, number of teeth, and number of teeth per inch (TPI), were recorded to ensure consistency between the impact blades. Weapon measurements were recorded before the tests to document length, width, blade length, blade width, bevelling and number of sharp edges (Table 1). Characteristics of the knife blades were measured using digital callipers. The average weight of the weapons was 840 g and the average length of the impact blades was 30.45 cm. The number of teeth per inch (TP) and the total number of teeth in the exposed blade were also recorded [25].

The samples were secured to a specimen plate with fabric coverings secured onto the fleshed specimens (unless unclothed) for impact testing. In this study, the serrated knife and scalloped knife were used to inflict stab wounds in a downward stabbing motion. The five fabrics were secured to the specimens and compared with unclothed samples. Two of each of the fabric samples, including the unclothed specimens, were examined with each weapon, resulting in four bones per fabric. Environmental conditions were recorded during tests and ranged between 75°F/24°C and 90°F/32°C. The average force of three drop-impacts per weapon was logged using the NEULOG 225 force plate sensor. The drop height of 0.6 meters was determined by examining the impact from various heights in order to determine a height that can be used to create an observable mark on the bone without shattering the bone. Fifteen cuts were made in approximately eight locations corresponding with the ribcage of the porcine specimen. Fifteen marks were made on specimens with two weapons and six fabric variables (including unclothed specimens), resulting in a total of 48 bones and 180 marks (90 marks per weapon).

After examining marks made on the fabric and flesh to determine if rib shattering was present, soft tissue was removed from the ribs by macerating the specimens using a biological detergent solution made from a 1:2 ratio of dish soap to water. The biological detergent maceration method was used because this method produces minimal damage to kerf marks [26]. Bones were suspended in the solution to avoid contact with the walls of the container and other bone specimens. The contained solution simmered on a hot plate for approximately three hours. The bones were removed, rinsed with distilled water, and the flesh was carefully removed. Bone surface features were examined in each rib specimen, as the bone surface has been shown to affect kerf

Weapon	Serrated	Scalloped
Weight (g)	860	820
Length (cm)	30.4	30.5
Width (cm)	2.54	2.54
Blade Length (cm)	4.825	5.014
Blade Width (cm)	1.527	1.751
Number of Teeth	40	8
Teeth Per Inch (TPI)	29	6
Beveling	Yes	No
Number of Sharp Edges	1	1

Table 1: Summary of weapon characteristics.

morphology and depth [26]. Features were scored and analyzed, but no significant association was found between bone features and weapon or fabric class. Porosity was analyzed by observing the presence of pores in the bone in numerous areas. Texture was recorded as smooth in samples with little variation in texture and a lack of an undulating appearance. Texture was recorded as textured where great variation in the topography was observed resulting in an undulating appearance. The gradient was determined by analysing the slope of the area surrounding the kerf mark. Level surfaces were categorized as having no gradient, slopes greater than 45° were classified as steep, and slopes below 45° were classified as shallow [27].

Photographs were taken of the kerf marks, and specimens were organized and labelled by weapon type, fabric type, and the impact test number. Kerf characteristics were then examined using a standard light microscope and recorded. Characteristics were scored based on the predetermined scoring measurements, and length was measured using digital sliding callipers.

## Results

The results were analyzed using several statistical tests, and all data were converted to z-scores to allow for analysis using SPSS 22 statistical software. Spearman’s rank order correlations were first run to see if any variables had a strong correlation with one another and could be grouped together. Striations and wall projections, cross-section and wall gradients [kerf shape], and margins and floor were positively correlated and, therefore, turned into z-scores and grouped together [r=0.459, r=0.454, r=0.333]. The weapon types were also positively correlated [r=0.621] and grouped together. Multivariate tests were run on the z-scores to examine weapon and fabric groups with kerf mark characteristics. Using statistical analyses, significance was set at less than or equal to 0.05.

A total of 180 marks were examined from fifteen marks in 48 bones and twelve fabric specimens [two specimens for each fabric]. The relationship between weapon type, fabric type, and kerf mark characteristics were examined using multivariate statistical tests. Kerf marks from specimens with fabrics were shown to significantly differ from kerf mark from unclothed specimens (Table 2). Kerf mark differences were exhibited through decreased width, decreased depth, decreased wall projections, and altered kerf shape resulting from shallower wall gradients in clothed specimens when compared to unclothed specimens. As the presence of lateral ridging was consistent in all marks, data on lateral ridging were not included in the analysis. Post Hoc tests revealed that fabric type differed on a statistically significant level in terms of affected kerf mark characteristics, including striations and wall projections, width, depth, and kerf shape (Table 3). Drill fabric samples exhibited the shallowest and smallest kerf marks with fewer striations and wall projections. Unclothed samples exhibited deeper and wider kerf marks with the most striations and wall projections. In addition, the kerf shape in drill fabric samples was also affected by the presence of steeper wall gradients. This suggests that the presence of fabric may alter the penetrative ability of weapons

Effect		Value	F	Hypothesis df	Error df	Significance
Intercept	Wilks' Lambda	0.785	5.181	30	835	0.001
Fabric	Wilk's Lambda	0.313	7.335	30	654	0.001
Weapon	Wilk's Lambda	0.626	16.23	6	163	0.001

Table 2: Multivariate tests on fabric types (comforter, satin, cotton, drill, polyester, and unclothed) compared to kerf characteristic patterns.

to create marks on bone. The null hypotheses assumed that there was no difference between specimens with fabric and flesh and de-fleshed, unclothed specimens with respect to kerf mark wall gradients, marginal distortion, width, depth, striations, and cross-section. The results of this study indicate that the null hypotheses can be rejected (Table 2).

Several significant findings were observed during this study. First, it was found that the standard serrated knife and scalloped knife showed statistically different results in striations and wall projections, margins and floor, and kerf depth (Table 4). Second, key observations on striation and wall projection effects were made. Results revealed that striations and wall projections differed significantly by fabric type (Table 4). The drill fabric and unclothed specimens significantly differed the most from the other fabrics, in terms of striations and wall projections (Table 3). Drill fabrics exhibited the most striations and wall projections, while unclothed specimens exhibited the least. Third, kerf width also significantly differed in fabric groups (Table 4). The widest marks were found in cotton [22%] and cotton comforter [23%] fabrics, and the narrowest marks were found in the thinnest coverings, including the satin [19%], polyester [19%], and unclothed specimens [18%]. Drill fabrics differed greatly from comforter and satin fabrics at a statistically significant level, in terms of width (Table 3). Drill and comforter fabrics displayed shorter widths than in satin fabrics. Fourth, differences in kerf depth were present. The shallowest marks occurred in the drill fabric [20%], and the deepest marks occurred in the unclothed specimens [20%] and polyester fabric [23%]. The results of the study further indicated that the interaction between depth variables differed within fabric groups at a statistically significant level (Table 4). Specifically, unclothed specimens differed at a statistically significant level from cotton, drill, and polyester fabrics (Table 3). Finally, the study revealed that V-shaped cross-sections were an observed characteristic of the standard serrated knives [100%], and very steep and steep wall

gradients were specifically common in marks made by the scalloped blade [28%]. The steepest wall gradients occurred in the drill [19%] and polyester fabrics [19%]. When examining kerf shape variables, it was found that kerf shape significantly differed from unclothed samples in comparison to clothed samples due to the presence of steeper wall gradients in unclothed specimens (Table 4). In respect to kerf shape, cotton and cotton comforter fabrics differed significantly (Table 3).

To assess the influence of intra observer error on results, validation tests were included in the study. One hundred and twenty random mark characteristics from the original dataset were examined microscopically and compared with the original findings. Intra observer error tests were run, revealing 91 out of 120 mark characteristics (76%) to be consistent with the original data. Weapon identification accuracy was 75% when compared with non-serrated and screwdriver cut marks.

### Discussion

The results of the study revealed that fabric type significantly affected striations and wall projections, kerf width, kerf depth, and kerf shape [including cross-section and wall gradients]. Each blade produced kerf marks that could be classified based on kerf width, depth, marginal distortion, wall projections, and fraying in fabric materials. The study additionally revealed that clothed specimens exhibited decreased width, depth, wall projections, and altered kerf shape resulting from shallower wall gradients when compared to unclothed specimens (Figure 2). As predicted, cut marks exhibited rounded features with projections and debris. Splitting was observed in the single-edged serrated blades, and serrated blades produced striations. This indicates that, despite the presence of fabric, splitting from the use of single-edged blades was still present in kerf marks. Furthermore, the presence of rounding, due to the elasticity of flesh, was consistent with research on fleshed specimens.

The downward thrusts from the drop-impacts tended to create a cone shape resulting from the shape of the knife point when impacting the bone and the scalloped blade tended to produce the most damage in kerf characteristics. Kerf marks made by scalloped blades could be distinguished from serrated blades by the presence of increased depths, steep wall gradients, and increased marginal distortion and debris. In addition, striation patterns from scalloped blades tended to be further apart and less concentrated than patterns in serrated blades. Despite these findings, variation in the results occurred. Scalloped blades exhibited a wider range of kerf characteristics than serrated blades. This could be attributed to fabric resistance from the blades snagging the fabric materials and varying rib sizes in the pig torsos used during

Dependent Variable	Fabric (I)	Fabric (J)	Mean Difference (I-J)	Significance
Striations and Wall Projections	Drill	Comforter	1.832	0.001
		Satin	1.756	0.001
		Cotton	1.171	0.002
		Polyester	1.373	0.001
	Unclothed	Comforter	2.391	0.001
		Satin	2.315	0.001
		Cotton	1.723	0.001
		Polyester	1.932	0.001
Width	Drill	Comforter	1.113	0.001
		Satin	0.726	0.045
Depth	Unclothed	Cotton	-1.19	0.001
		Drill	-1.19	0.001
		Polyester	-1.035	0.001
Kerf Shape	Comforter	Cotton	0.844	0.045

Table 3: Fabric post hoc tests for striation and wall projection kerf patterns, kerf width, kerf depth, and kerf shape.

Effect	Dependent Variable	N	F	Significance
Fabric Type	Striations and Wall Projections	180	21.731	0.001
	Width	180	3.841	0.001
	Depth	180	8.417	0.001
	Kerf Shape	180	2.359	0.042
Weapon Type	Striations and Wall Projections	180	10.56	0.001
	Margins and Floor	180	5.455	0.002
	Depth	180	2.734	0.003

Table 4: Test of between-subjects effects for weapon and fabric effects on kerf striation and wall projection patterns, kerf width, kerf depth, and kerf shape.

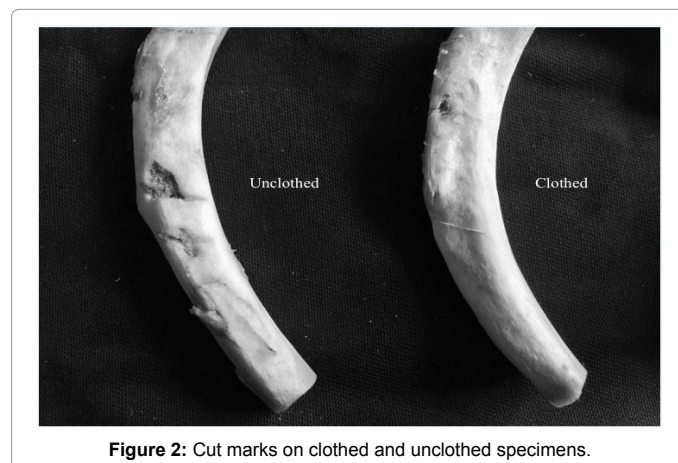


Figure 2: Cut marks on clothed and unclothed specimens.

the study. Furthermore, though drop-impact tests were useful in controlling the force of impact, the trajectory and angle of the blade may still have affected kerf mark appearance. Fabric specimens provided variable results, making classification more difficult. However, the most useful diagnostic feature in identifying fabric materials resulted from the presence of embedded fibres and fabric debris that was not visible macroscopically but present in the majority of kerf marks.

The current study confirmed findings by Symes et al., Potts and Shipman, Blumenschine et al., and Alunni-Perret et al. that suggested serrated blades produce V-shaped cross-sections [8,17,18,22]. Sharp force trauma validation studies have indicated that U-shaped marks are not a diagnostic feature of serrated knife kerf marks. However, this study indicated that scalloped blades produced U-shaped cross-sections in addition to commonly found V-shaped cross-sections, suggesting that the creation of U-shaped marks may not automatically rule out serrated knives. This challenges literature findings that suggest V-shaped cross-sections are the only cross-sectional characteristic of serrated and scalloped knives. Furthermore, the highest number of deep cut marks and cut marks with varied depths were found in scalloped blades. This may be a result of teeth “skipping” as the blade hits the surface, causing variation in cross-sectional shape [28]. The combination of U-shaped cross-sections and varied depths associated with scalloped blades signifies that blade skipping, that is more likely to occur in scalloped blades, were demonstrated to have an impact on kerf mark characteristics. These findings highlight the need for more research to assess the validity of distinguishable characteristics between clothed and unclothed samples and to improve kerf characteristic assessment difficulties due to surface debris.

This research has several significant implications in the field of forensic anthropology. First, distinguishing between serrated and scalloped knives was possible using cut mark classification criteria. Second, fabric was shown to have an effect on the appearance of cut marks on bone. The prevalence of sharp force trauma crime indicates that this research and other sharp force trauma studies are applicable to research in forensic settings. This research can assist in the determination of violent scenarios and contexts of homicide investigations by assessing whether victims were clothed or unclothed during attacks or if perpetrators have attempted to destroy evidence on apparel. These factors are especially important in domestic violence related homicides and assaults where victims may have clothing removed during or after attacks.

The results of this experiment foster several recommendations and considerations for future research. Depth is a variable that has seldom been addressed in research when compared to other variables. While depth was addressed in the current study, characteristics were only superficially analyzed. Debris may also obscure depth measurements. Future research on sharp force trauma should analyse depth characteristics further and determine whether this variable can be used to develop consistent classification criteria. Future studies might analyse cut marks made at a fixed depth to establish whether significant differences are found between weapon classes. Guided-drop tests were useful in this experiment; however, human stabbing behaviours in relation to cut marks can be analyzed in future research as well. Finally, the inclusion of additional bedding fabrics is suggested in future sharp force trauma studies.

In conclusion, this research indicated that it is possible to classify cut marks by weapon and fabric type based on trauma characteristics left on bone. Although there is variation and subjectivity in the classification of kerf features, analysing all features in conjunction

with each other can assist greatly in the forensic identification process. The use of a guided-drop device was necessary for this research as it allowed for consistent force and directionality when producing cut marks. This study also found standard light microscopy to be a cost-effective and accessible option for analysing cut marks on bone. Most significantly, this study challenges current data on cross-sections from serrated knives and highlights the variability in kerf characteristics resulting from fabric resistance. As the use of bedding fabric has not been consistently analysed in sharp force trauma studies, this research provides data applicable to a variety of forensic examinations that have not been adequately addressed.

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