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Effects of heat on cut mark characteristics

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ABSTRACT

Cut marks on bones provide crucial information about tools used and their mode of application, both in archaeological and forensic contexts. Despite a substantial amount of research on cut mark analysis and the influence of fire on bones (shrinkage, fracture pattern, recrystallisation), there is still a lack of knowledge in cut mark analysis on burnt remains. This study provides information about heat alteration of cut marks and whether consistent features can be observed that allow direct interpretation of the implemented tools used.

In a controlled experiment, cut marks (n = 25) were inflicted on pig ribs (n = 7) with a kitchen knife and examined using micro-CT and digital microscopy. The methods were compared in terms of their efficacy in recording cut marks on native and heat-treated bones. Statistical analysis demonstrates that floor angles and the maximum slope height of cuts undergo significant alteration, whereas width, depth, floor radius, slope, and opening angle remain stable.

Micro-CT and digital microscopy are both suitable methods for cut mark analysis. However, significant differences in measurements were detected between both methods, as micro-CT is less accurate due to the lower resolution. Moreover, stabbing led to micro-fissures surrounding the cuts, which might also influence the alteration of cut marks.

1. Introduction

1.1. Cut mark analysis in archaeology and forensic science

The analysis of cut marks is instrumental for interpreting the manner, and potentially, the cause of sharp force trauma in forensics and archaeological contexts. Furthermore, it allows drawing conclusions about the implement used and can help to characterise the tool class, and in certain cases even the identification of specific, individual tools. This is helpful to match the weapon used with the wounds on the victim in crime investigations.

In archaeological human remains cut marks are usually related to acts of violence, sacrificial or otherwise mortuary behaviour, whilst animal remains show cut marks from butchering [1–7]. In forensic investigations, the analysis of cut marks is of major importance for crime investigation as, for example, stabbing is the most common method of homicide in Britain [8–10], where a knife was used for the assault in 53% of all murder cases [7]. The most common weapon in stabbing is a long, slender, and double-edged knife, such as common household knives [11,12]. As prime target for attacks, the chest is the most vulnerable body area [6,8].

Stabbing is a complicated sequence of different movements, which produces axial and non-axial forces and torques, that are difficult to reproduce in an experimental context [13,14]. This is the main reason why only little research has been conducted so far. Besides these forces, the shape and geometry and the sharpness of the knife blade tip, the velocity of the attack and resistance factors, such as clothing and bones have a crucial impact on the injury of the victim [13,15–19].

Once cut through the skin, no more force on the knife is required to penetrate deeper into soft tissue [20]. In general, a force of about 5–29 N [15,16] is necessary to spike human skin. However, these are just minimum values. Beside the stabbing forces, it is even more important to define the characteristics of cut marks. There are many features that can be measured to describe the form of cut marks. Generally speaking, sharp metal blades produce V-shaped kerfs and clear apices [21], whilst scrapping and slicing cuts create U-shaped pits [22].

Several case studies emphasize the importance of cut mark analysis and the examination of burnt remains [23,24]. In forensic settings, usually bone fragments and, sometimes, soft tissue will be encountered, but depending on experience and time, a body can be burnt completely so that only calcined bone fragments remain

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[24]. However, often the corpse is just deluged with petrol and inflamed, which only leads to charring of the outer surface.

1.2. Heat alteration of bones

When bone is burnt, various extrinsic (temperature, time, oxygen, humidity) and intrinsic factors (bone composition, soft tissue, pathological lesions, injuries, age) are responsible for fracturing, shrinkage, deformation and weight loss. In general, heat alteration leads to a removal of organic compounds and a reorganisation of inorganic material [25]. The impact of heat depends on the oxygen supply, the thickness of soft tissue and other protective materials [26,27]. Mayne Correia [28] summarised the effects of heat induced changes, which were later slightly revised by Thompson [29]. They observed four stages of transformation: first the bone dehydrates, which is followed by pyrolysis of organic compounds and inversion, which is the loss of carbonate. Finally the inorganic compounds start to fuse.

Dehydration leads to warping and cracking of the bone [30–34]. Between 600 °C and 800 °C the organic compound is completely burnt and the contraction of the bone structure increases [32,33]. In the literature the total amount of shrinking varies between 0.5 and 27% [25,31,35,36]. Accompanied by shrinkage and colour alteration, the carbonate concentration decreases from 6% in raw bones to approximately 1% in calcined bones [37,38].

Finally, it has to be considered that in reality it is quite difficult to completely burn a corpse: camp fires burn at 400 °C and rarely reach 700 °C [39]. House fires gain 700 °C, burning cars and crematoria around 1000 °C [24,31]. However, because of the thin layer of soft tissue of the chest and head, the rib cage and facial bones are revealed within 20 min, if the body is heated up to 650 °C [40]. Therefore a careful analysis of burnt ribs is important in many cases, because injuries may be destroyed quicker than on other body parts, which are covered by thicker layers of soft tissue. Usually a body is fully cremated in 3 h at a temperature between 670 °C and 810 °C in a cremation furnace [41].

Heat fractures can be longitudinal, transverse, delaminated or reticulated. Transverse fractures usually occur due to the shrinkage of soft tissue [42]. Other fracture types present as small, reticulated cracks of the outer bone surface and delamination, a separation of different bone layers is often observed between cortical and spongy bone [43].

1.3. Innovations of cut mark analysis

Whilst many studies have focused on stabbing, cut mark analysis and heat induced bone alteration, only little research has been conducted on cut marks of burnt remains [43–45]. Frequently, only the presence or absence of cut mark structures was determined [46]. Other researchers suggested, that cut and saw marks on burnt remains can be identified and a determination of the type of tool is possible, although fire can alter and modify peri-mortem trauma [47–50].

Pope and Smith [44] observed the alteration of soft tissue around cut marks and noted that as the soft tissue is damaged above cut marks, the skin tends to split and form a bulge. This leads to shrinkage of the soft tissue lesion; the underlying bone is exposed and will be altered by the heat sooner and quicker as the bone is no longer protected by soft tissue.

Various methods have been used to analyse cut marks. Initially, light microscopy and SEM were employed [7,29,33,51–64], while recent years seen more sophisticated 3D-methods, like computer tomography (CT) [65–67]. However, Bello and Soligo [68] and Thompson and Chudek [69] point out that SEM is a destructive method and only provides 2-dimensional images.

In comparison to micro-CT, 3D-microscopy is an efficient method in terms of implementation, speed and costs, which renders it an ideal tool for cut mark analysis [21,68]. Even complex structures, such as micro-striations can be evaluated and measurements of cross sectional profiles allow a careful evaluation and have led to the application of 3D digital imaging techniques in various studies [61,68,70,71].

1.4. Pigs as a model for humans in forensic science

For various reasons, research on trauma and decomposition cannot be done with human cadavers in the UK. Often, pigs are often chosen as human analogues in forensic experimental studies [45,64,65,72,75–79]. Pig skin has similar mechanical characteristics to human skin, but it is thicker and contains more collagen, which makes it more flexible [15,16,80–84]. However, the mineral density is much less in pig bones than in humans [84,85]. As pigs used are still juvenile and a 40 kg pig has the same bone mineral density as an 8–10 year old child [86].

The aim of this study is to provide a novel approach to analyse heat alteration of cut marks by identifying how cut marks on bone are affected by high temperatures.

The following hypotheses will be tested:

- Cut marks are shrinking upon heating as previous research revealed shrinkage of bone due to a loss of organic material.
- Digital microscopy and micro-CT are both suitable methods to analyse cut marks and deliver similar results.
- There are correlations between fissures beneath the cut mark floor and the cut mark depth.

2. Material & methods

For this study, a rack of pig ribs, covered with soft tissue from a nine month old pig (Sus scrofa domesticus), were obtained from a butcher. Due to the juvenile stage, which is supported by the visibility of non-fused epiphyses, the bones contain a higher amount of organic material and are less mineralised as compared to adult pigs [87]. The sample included the 2nd to the 11th rib, cut off close to the sternal rib end but not containing any rib cartilage. The rib sample measured approximately 29 cm in length and 8 cm in width. The soft tissue above the ribs had a thickness of 43 mm. The rack was divided into three parts, each containing three ribs, and subjected to the experiment.

In order to achieve maximal reproducibility for the experimental setup, different interfering variables had to be excluded beforehand or at least minimized. A well-known factor difficult to copy in an experimental setup is stabbing, as: the literature suggests different forces, movements and differences between single human offenders [15,88,89]. Therefore a simple gadget was built, which works similar to a guillotine to create equal cut marks on the ribs (Fig. 1). Three cooking knives (Ikea, model Vörda) with a total length of 340 mm, a blade length of 207 mm and a weight of 147 g, respectively, were used for the experiment. The knife's spine is 190 mm long and the blade's height measures 48 mm in maximum. The knife's blade is straight on its first third next to the handle and non-serrated. The second third is slightly curved and its last third is strongly curved upwards. The knife's spine is not straight and is slightly curved towards the edge. The knife-edge has a total angle of 14° with a floor radius of 12 μm. Additionally, weights of 1 kg, each, were attached to either side of the blade to create more realistic forces. Thereby, the overall weight of the falling sliding carriage, including the knife was 2404 g, which is equal to a force of 24 N respectively.

Knives were replaced for the cutting of every rib sample (containing three ribs) after 11 cut marks to minimize variation of

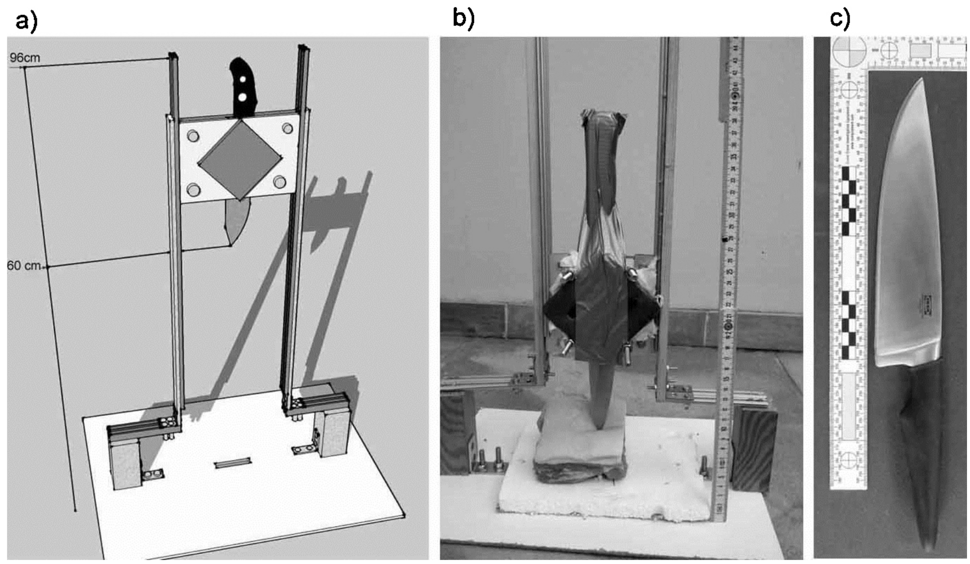

Fig. 1. Guillotine. (a) Computer model of the used guillotine, (b) the guillotine and its functionality, (c) used cooking knife (Ikea, model Vörda).

the cut marks due to a damaged blade. The guillotine was calibrated in a way that the knife tip would hit the skin slightly above the superior rib margin and only incise the rib surface instead of penetrating it completely. This was important as a pilot study showed that, if the knife blade hit the rib directly, the tip of the knife would break and get stuck into the bone, and the knife blade itself bent. Therefore, just the cut appearance could be observed in this study.

The setup used here is a common scenario emerging in stabbing, because a direct strike on the rib leads to a light injury instead of a penetration of the knife into the rib cage. During and after the entire procedure, the tissue was kept humid to avoid dehydration and subsequent, which may influence the burning process. The knife was manually released from a dropping height of 64 cm, measured from the floor to the tip of the knife to receive a calculated maximum force of 24 N. After the experiment, the tissue was shrink-wrapped and immediately frozen.

For the second stage of the experiment, the samples were divided into two sets: while the first set was kept frozen until burning, the other half of the sample was defrosted and the majority of the soft tissue was removed. The ribs were then macerated in water for three weeks at a temperature of 25 °C.

All samples were burnt in an electric Carbolite OAF-11/1 furnace (3900 W) at 700 °C for three hours. They were put inside the cold furnace and heated up. When the temperature reached 700 °C, the sample remained in the furnace for three hours, which was considered as being sufficient to burn all organic material, as Bohnert et al. [41] showed, that all soft tissue, which covers the ribs, will be burnt within 20 min at 670 °C–810 °C during the cremation process and a whole body can be burnt within three hours. After three hours, the samples were taken out of the furnace and cooled down at room temperature.

The first analysis of the macerated ribs and the second analysis of the burnt bones were undertaken using a Keyence VHX-5000 digital microscope. All cut marks were examined at a magnification of 200-fold, using a VH-Z20R/W lens. High resolution 3D-profiles were created using scanning levels for every 5 μm. Every 400 μm, one cross section of the cut mark was measured perpendicular to the longitudinal axis of the cut. The ends of the cut marks were excluded, because they were too fine for the resolution of the method used. All pictures were captured with a resolution of 3200 × 2400 pixels.

The following features of the cut marks were measured (Fig. 2):

Cut mark depth (CMD): The perpendicular depth from the deepest point of the cut mark floor to the natural bone surface. If the edge was rounded, the depth was calculated up to that point in which the elongations of the cut mark wall and the bone surface are crossing.

Maximum shoulder height (MSH): The perpendicular height from the deepest point of the cut mark floor to the top level of the higher margin, if the margin was bulged by the knife.

Cut mark width (CMW): The perpendicular width between the margins of the cut mark on the bone surface.

Cut mark length (CML): The maximum length of the cut mark, measured at the cut mark floor.

Slope angles (SA): The angle between the natural bone surface and the slopes. Measured on the right (SA_R) and left side (SA_L).

Opening angle (OA): The angle between both cut mark walls.

Floor radius (FR): The radius of a circle fitted to the cut mark floor. Here the floor lies between two points, where the slopes start to converge [68].

Floor angles (FA): The angle between the slope and the cut mark floor, where a line intersects the deepest point and the point, where the slope starts to converge. Measured on the left (FA_L) and right side (FA_R).

Additionally, one macerated rib was scanned using a Viscom X8060 II micro-CT. This data set was taken to allow an evaluation whether micro-CT would be a suitable or even better method than digital microscopy. The sample was surveyed in 1440 images, which were made every 0.25° rotation at a resolution of 15 μm. Finally, the data were analysed using Amira [90], 3D-Slicer [91] and Fiji [92].

All variables that describe the proportions of cut marks were analysed to identify differences between the control and the experimental sub-sets. For this, the type of distribution was first examined and possible outliers were identified. Normal distribution of obtained data was tested using the Shapiro–Wilk test. Outliers were found in the following variables: burnt depth, unburnt width, and in the right slope angle in the control and the experimental group.

3. Results

The colouration of burnt ribs varied from bluish-grey to white. Although the samples were very fragile and of a chalky appearance,

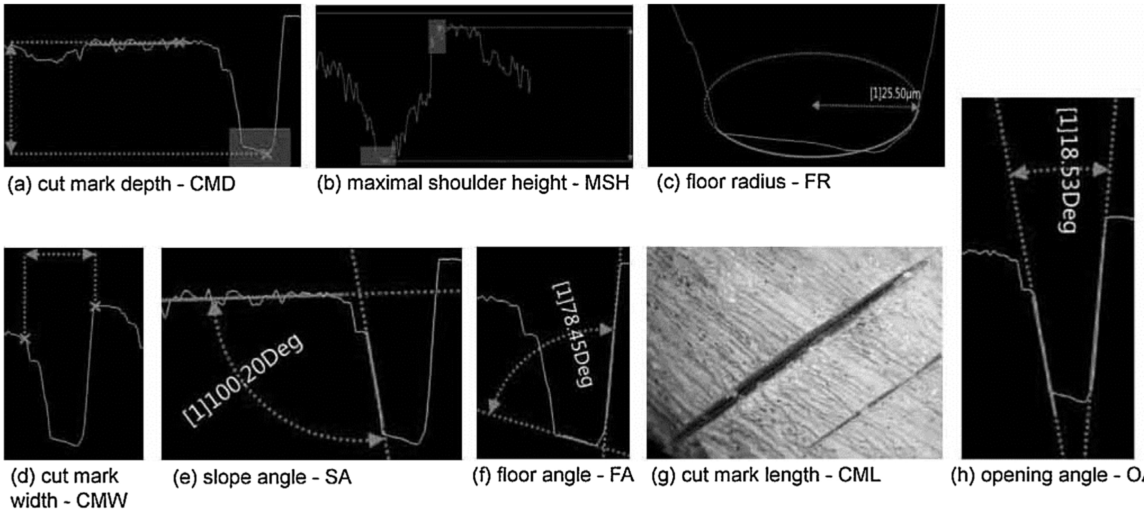

Fig. 2. Measured variables. (a) Cut mark depth (CMD), (b) maximal shoulder height (MSH), (c) floor radius (FR), (d) cut mark width (CMW), (e) slope angle (SA), (f) floor angle (FA), (g) cut mark length (CML), (h) opening angle (OA). Wiggly lines represent the shape of the cross sections and crosses at these lines were used to measure distances (broken lines).

fragmentation did not occur in the furnace, but longitudinal heat cracks appeared at the surface of the experimental set (burnt with flesh). A slight striation was recognized on the walls of one burnt and two unburnt cut marks. The walls of all other cuts remained smooth.

Seven ribs were analysed in total: four of them were macerated and ten cut marks analysed in this control set (unburnt). For the experimental sub-set, three ribs were burnt with flesh and 15 cuts were examined. Overall, 199 cross sections were examined (74 in the control set and 125 in the experimental set). Approximately every 400 μm one cross section was evaluated. On average, an unburnt cut mark was 8.4 mm (SD = 2.72) long, 380 μm deep (SD = 221.44) and 280 μm wide (SD = 124.50). The floor radius is 30 μm wide (SD = 13.03). In comparison, after burning, cut marks were 6.3 mm long (SD = 2.44), 466 μm deep (SD = 545.39) and 239 μm wide (SD = 84.48) and contained a floor radius of 24 μm (SD = 16.03). Slope angles were 106°–111° (SD_{left} = 21.40; SD_{right} = 16.98), floor angles 121°–122° (SD_{left} = 21.90; SD_{right} = 27.19) and opening angles were 20° wide (SD = 12.12) in the control group. In the experimental group in contrast, slope angles were 100°–107° (SD_{left} = 22.26; SD_{right} = 19.25), floor angles around 134° (SD_{left} = 24.50; SD_{right} = 19.77), and opening angles were 21° wide (SD = 11.80, Table 1). Many cut mark floors obviously cracked during the cut mark production or the burning process and hence floor features could not be measured. Therefore the term “floor destroyed”, was introduced for these samples to collect their data.

Significant differences between unburnt and burnt cut marks were found in both floor angles (left side: Mann–Whitney U-test: n = 88, p = 0.031; right side: Welch’s t-test: n = 86, p = 0.046) and in the maximal shoulder height (Welch’s t-test: n = 31, $p < 0.001$; Fig. 3). In all other variables no significant heat alteration was detected.

Floor and slope angles of the cut marks were examined to test whether there was a linear correlation between left and right side. If the knife hits the bone exactly vertical, both sides should be symmetrically. In contrast, if the knife hits the rib obliquely from left to right, the angle should be smaller on the left side and vice versa. No correlation was found for slope angles (unburnt: 2-tailed

Table 1
Descriptive statistics of unburnt and burnt cut mark features (in μm).

	n	Range	Minimum	Maximum	Mean	SE of mean	SD	Variance	Skewness	SE of skewness	Kurtosis	SE of kurtosis
Unburnt												
CMD	53	830.40	56.84	887.24	370.73	30.42	221.44	49,035.603	0.722	0.327	−0.331	0.644
CMW	67	634.25	70.60	704.85	280.02	15.21	124.50	15,499.277	0.994	0.293	1.729	0.578
MSH	17	1306.03	173.54	1479.57	781.41	98.20	404.87	163,923.399	0.225	0.550	−0.950	1.063
FR	22	45.36	7.92	53.28	29.68	2.78	13.03	169.722	0.240	0.491	−0.741	0.953
FA_L	34	90.67	77.72	168.39	123.24	3.76	21.90	479.619	0.220	0.403	−0.403	0.788
FA_R	36	102.94	66.39	169.33	121.92	4.53	27.19	739.109	−0.245	0.393	−1.066	0.768
SA_L	59	81.11	69.67	150.78	106.49	2.79	21.40	457.910	0.131	0.311	−0.751	0.613
SA_R	55	78.39	64.19	142.58	110.92	2.29	16.98	288.336	−0.447	0.322	0.375	0.634
OA	52	43.46	4.46	47.92	19.95	1.68	12.12	146.862	0.597	0.330	−0.673	0.650
CML	10	9807.00	3345.00	13,152.00	8389.86	861.31	2723.69	7,418,488.442	−0.199	0.687	0.594	1.334
Burnt												
CMD	82	2860.93	31.07	2892.0	466.36	60.23	545.39	297,449.114	2.532	0.266	7.557	0.526
CMW	114	358.08	76.97	435.05	238.98	7.91	84.48	7136.709	−0.178	0.226	−0.639	0.449
MSH	14	556.35	69.81	626.16	278.90	43.88	164.17	26,953.339	0.720	0.597	−0.060	1.154
FR	52	61.69	3.00	64.69	24.45	2.22	16.03	257.074	0.873	0.330	−0.070	0.650
FA_L	54	97.08	76.88	173.96	133.60	3.33	24.50	600.364	−0.542	0.325	−0.557	0.639
FA_R	50	76.12	93.81	169.93	132.77	2.80	19.77	390.874	−0.137	0.337	−0.668	0.662
SA_L	108	109.82	43.35	153.17	100.03	2.14	22.26	495.360	0.147	0.233	−0.548	0.461
SA_R	104	95.55	55.86	151.41	107.09	1.89	19.25	370.594	−0.400	0.237	0.358	0.469
OA	69	48.86	3.40	52.26	20.88	1.42	11.80	139.312	0.740	0.289	0.096	0.570
CML	14	8178.00	2277.00	10,455.0	6333.00	653.22	2444.12	5,973,718.769	−0.052	0.597	−0.767	1.154

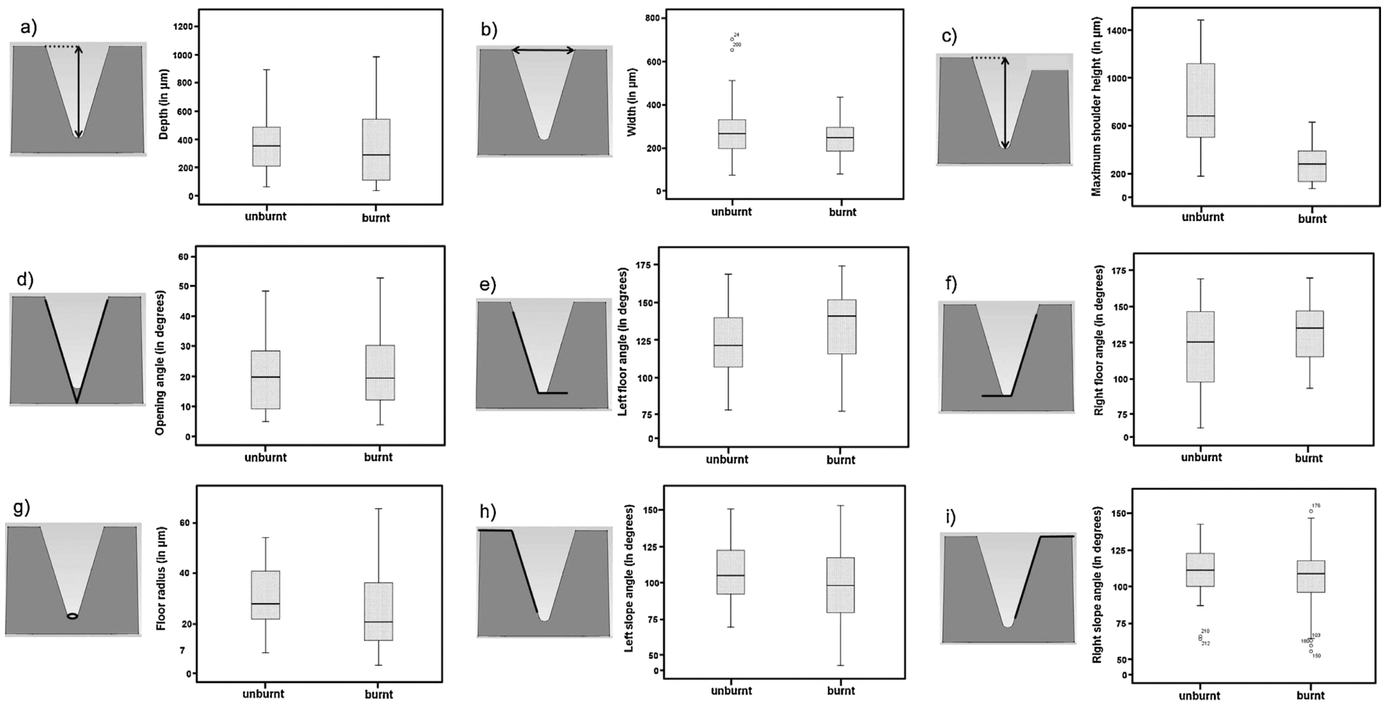

Fig. 3. Observed heat alteration between the unburnt and burnt group. (a) Cut mark depth, (b) cut mark width, (c) maximum shoulder height, (d) opening angle, (e) left floor angle, (f) right floor angle, (g) floor radius, (h) left slope angle, (i) right slope angle.

Pearson correlation: $n = 50$, $R = 0.156$, $p = 0.280$; burnt: 2-tailed Pearson correlation: $n = 95$, $R = 0.077$, $p = 0.461$) and in the experimental group for the floor angles (2-tailed Spearman correlation: $n = 45$, $Rho = 0.273$, $p = 0.07$). However a significant correlation was detected for left and right floor angle in the unburnt sample (2-tailed Pearson correlation: $n = 30$, $R = 0.464$, $p = 0.010$, Fig. 4).

Moreover, a significant correlation was found between the depth and the destruction of floors: First, the data for burnt specimens were divided into two groups, separated by the mean to reduce the amount of cells in the cross table, which is necessary to calculate a Chi^2-test. In the half with a depth over 366.35 µm, more cross sections and in the other group less cross sections with damaged floors were detected than expected ($n = 120$, $Chi^2 = 30.543$, $p = 0.001$, Fig. 5).

Additionally, the micro-CT data were evaluated to assess a correlation between cortical thickness and fissures, which are located beneath the cut mark floor (Fig. 6). For this, an index was developed to combine the total cortical thickness and the cortical thickness beneath the cut mark floor as both factors might be important for its breakage:

$$\frac{\textit{total cortical thickness}}{\textit{remained cortical thickness beneath the cut mark floor}} \times 100$$

Like for the correlation between the cut mark depth and the destroyed floors, these data were divided into two groups, separated by the median to fulfill pre-conditions. Within these groups no correlation was detected (exact Fisher test: $n = 22$; $p = 0.090$). Additionally, cracks in the area around fresh (unburnt) cut marks were detected on micro-CT images. These stress fissures are signs of the high-energy impact of the knife blade on the bone surface (Fig. 6).

Finally, the micro-CT data were compared to the data obtained by digital microscopy to evaluate whether both methods are suitable for cut mark analyses and if they would provide similar results. As an unburnt rib was scanned, it was compared to the control group. No differences were found in the maximum shoulder height ($n = 41$, $p = 0.653$) and the opening angle ($n = 80$; F-test: $F = 7.918$, $p = 0.006$; Welch's t-test: $p = 0.769$). However, significant discrepancies were found in depth (Mann–Whitney U-test: $n = 81$, $p = 0.043$), width (Mann–Whitney U-test: $n = 95$, $p < 0.001$) and both slope angles (left: $n = 87$; F-test: $F = 5.292$, $p = 0.024$; Welch's t-test: $p < 0.001$; right: Mann–Whitney U-test: $n = 83$, $p < 0.001$, Fig. 7). Floor features could not be measured because the resolution was not sufficient.

Additionally, twenty cross sections obtained through digital microscopy were randomly chosen and measurements were repeated six times to assess the technical error in the evaluation of every single variable (Table 2). Furthermore, statistical analysis revealed no significant differences in measurements within any trait.

Table 2
Calculated Error of measurements and their variations: six repeat measurements per variable were taken from randomly chosen cross sections.

Variable	Minimum	Maximum	Mean	SE	SD	Variation
Unburnt						
CMD	428.05	430.50	429.24	0.37	0.89	0.800
CMW	310.89	313.34	312.38	0.39	310.89	0.909
MSH	424.91	426.70	426.19	0.30	0.72	0.523
FR	102.13	104.99	103.53	0.41	1.00	1.013
FA_L	96.54	98.17	97.46	0.29	0.72	0.520
FA_R	99.50	102.07	100.72	0.42	1.02	1.055
SA_L	79.16	80.08	79.57	0.14	0.34	0.112
SA_R	99.10	100.91	99.96	0.28	0.70	0.484
OA	46.04	47.58	46.57	0.22	0.55	0.297
Burnt						
CMD	508.94	513.67	511.3	0.86	2.10	4.418
CMW	141.12	143.18	142.17	0.30	0.72	0.523
MSH	1121.72	1127.14	1124.73	0.89	2.18	4.774
FR	22.50	22.93	22.73	0.08	0.19	0.035
FA_L	78.47	80.38	79.47	0.30	0.75	0.556
FA_R	92.82	96.82	95.15	0.56	1.37	1.867
SA_L	103.34	106.75	104.56	0.51	1.25	1.573
SA_R	87.40	88.67	87.87	0.19	0.46	0.214
OA	27.32	29.69	28.42	0.34	0.83	0.696

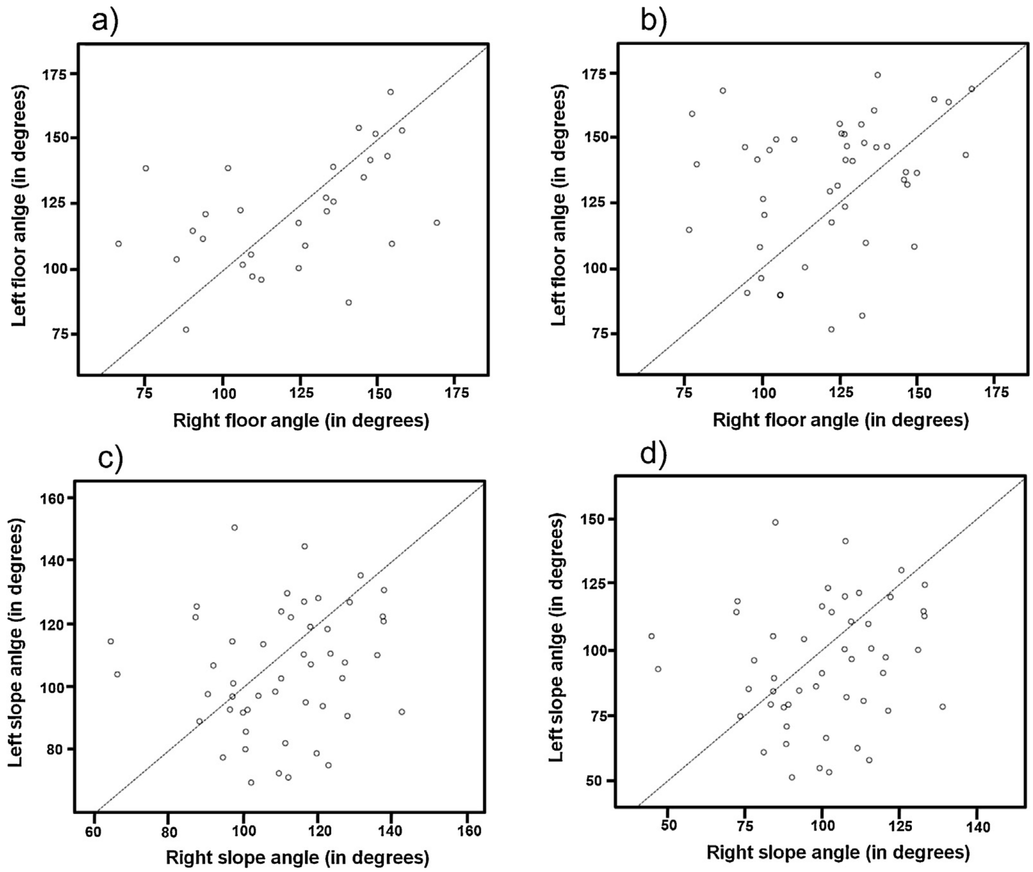

Fig. 4. Correlations between left and right side: (a) unburnt floor angles, (b) burnt floor angles, (c) unburnt slope angles, (d) burnt slope angles.

Furthermore, the results highlighted one cut mark with outliers (rib three—cut mark three): the rib fragmented alongside the cut mark floor cut. As one side of the cut mark slope was not damaged, it was possible to take a few measurements. However, statistic analyses revealed these measurements as outliers and it seemed that the depth of this cut mark was overestimated due to an error in measurement. Further, in measurement 109 the floor splits and therefore the floor angles could not measured accurately. Therefore these measurements were excluded from analysis.

The cut mark length was not statistically evaluated, due to a small sample size of five and a high variability, as this feature is strongly dependent on the location at which the knife hit the bone.

4. Discussion

After heat exposure, cut marks on ribs remained surprisingly stable and did not change much. Although, various studies demonstrated that bones shrink during heat treatment [25,26,28,29,31,35,36,73,74,90,91], this does obviously not result in strong alterations of cut marks. Thereby, many cut mark traits are still suitable for forensic and archaeological analyses even in burnt specimens and can be treated in the same way as cut marks on fresh bones. Cut mark depth, slope angles and opening angles were not significantly altered. However, the variability increased in all variables, except in the width. Whilst it is difficult to determine

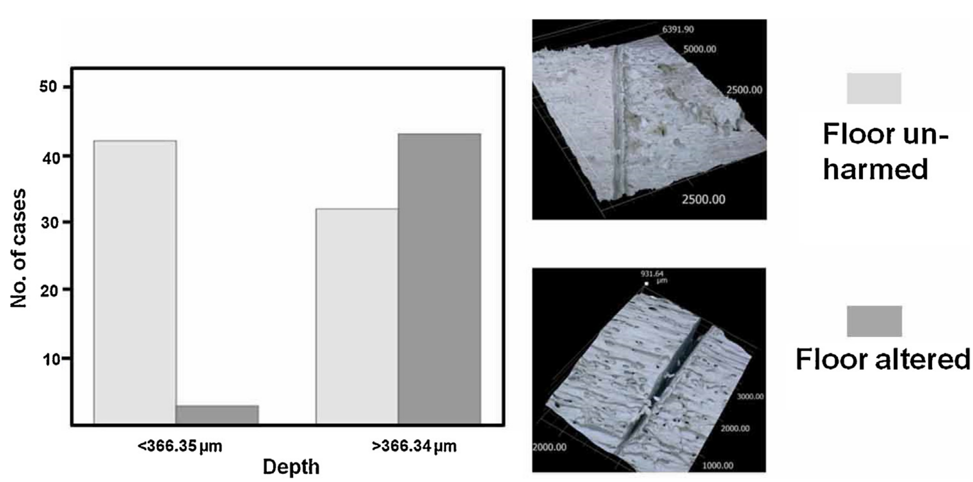

Fig. 5. Correlation between the cut mark depth and the destruction of the cut mark floor.

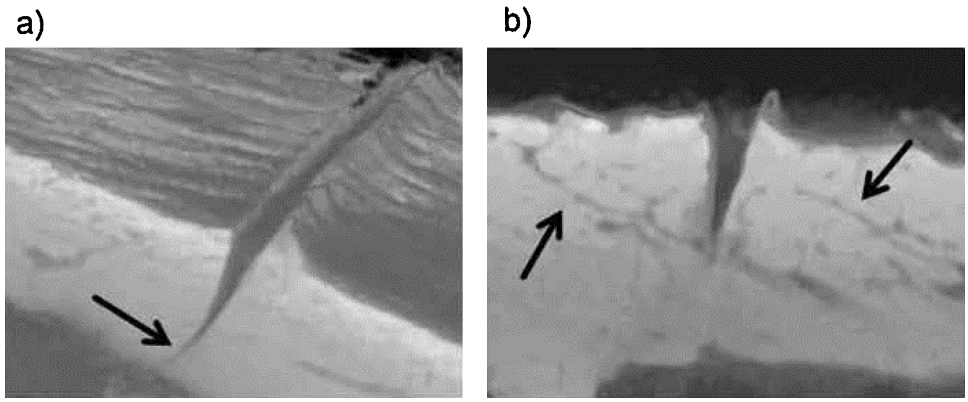

Fig. 6. Stress fissures on 3D-reconstructions of fresh (unburnt) cut marks (micro-CT). (a) Fissure beneath the cut mark floor. (b) Small cracks in the area around a cut mark are signs of energy absorption of the knife impact.

the exact reasons for this effect, it is likely that these are indeed faint signs of heat alteration.

Heat alteration was observed in the floor angles and the maximum slope height. As the maximum slope height primarily describes the effects of bulged bone, which represents a slight rotation of the knife during the stabbing process [45], these areas are composed of bone fragments, which are only partially connected to the bone surface as the micro-CT scans revealed. Due to the incision in flesh, cuts are more exposed to heat [44]. The cracks broadened and small particles of the bulged bone broke off [45]. The appearance of bulged bone is a sign that the experiment did not produce completely controlled conditions. Since the knife was fixed and not able to move in the apparatus, the rotation would have been caused by the sample itself, because the soft tissue is flexible and thus moved slightly from the impact of the knife. Although it would be difficult to control this condition, the observations suggest that cut marks were in fact produced in a more realistic way than a completely controlled experiment and therefore are more meaningful for an application to real cases.

Further significant changes were detected in both floor angles, but interestingly not in the slope angles. If this effect would be caused only by heat treatment, it might be explained with irregular bone shrinkage and therefore a warping of the cut mark shape. However, these effects would be expected to appear in all angles and not only at certain parts of the cut. Therefore, the samples were analysed for correlations between both slope and both floor angles to detect irregularities before the heat treatment. No correlations were found in the slope angles. That is caused by random up warping of the bone surface during the knife rotation in the wound.

The rotation of the knife affects the slope angle at only one side and thereby it eliminates any correlation independent of the burning effect. On the contrary, a significant correlation was found

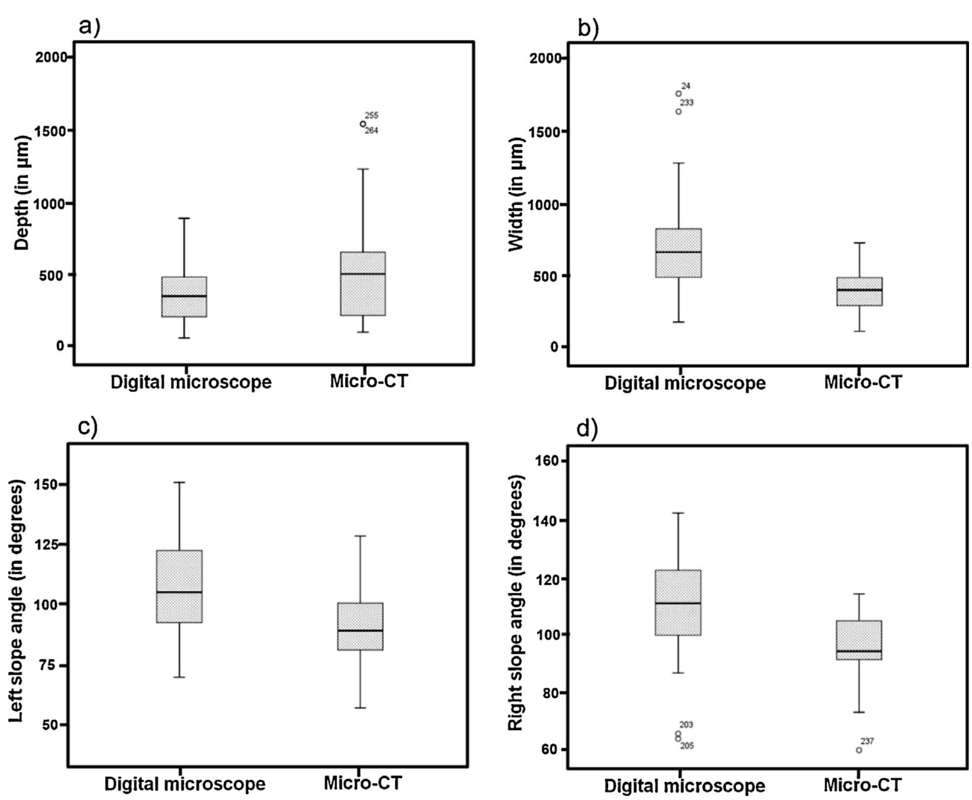

Fig. 7. Significant differences between data collected by micro-CT and digital microscopy. (a) Cut mark depth, (b) cut mark width, (c) left slope angle, (d) right slope angle.

between the unburnt floor angles but could not be observed in the burnt sample. It seems that the knife rotation affected the slopes but had only a small effect on the floor. This confirms the above posed hypothesis that these fissures, as seen on the micro-CT scans, can influence the cut mark floor if burnt. It is likely that these cracks widened during the heat treatment or were more strongly affected by bone shrinkage as a consequence of the reduced tension in the damaged bone, which influenced floor angles in an irregular way. Therefore the ratio of angle size between left and right side changed and weakened the correlation. As a detailed analysis would be needed to compare single cut marks in unburnt and burnt situations, this question could not be answered completely in this study. A correlation of the cut mark depth and the condition of the floor (destroyed and unharmed) revealed significantly more cracks of floors beneath deep cut marks. Particularly in these cases, it was found that the cortical thickness strongly influenced the appearance of cut marks. However, more research has to be done on this question.

The CT-scans demonstrated that the knife partially cut through nearly the whole layer of compact bone. In these areas the knife penetrated deep into the bone as it hit the bone stronger and more directly instead of sliding along the edge. Moreover, the compact bone was thin at these positions. Another reason for these deep incisions is that the knife blade was larger than the gap between two ribs and so the neighbouring rib performed additional pressure on the knife during the stabbing process, which also supported a deeper penetration of bone. Additionally, pig ribs are more robust than human ribs. This is another important factor for knife penetration, as the cortical bone is very dense and prohibits a deep penetration. In contrary, in humans, it would be expected that the knife will cut through the complete compact bone, because in humans this layer is much thinner than in pigs. Therefore, fissures of the cut mark floor and destroyed floor features are more likely to develop in humans than in pigs.

Although stabbing forces and flesh thickness, bone composition, etc. are quite similar in pigs and humans [15,80–86], there are some crucial differences, which are important to mention in this context: as pigs are slaughtered as juveniles, the bone composition is different to adults and the bone also contain a higher amount of organic compounds [86]. However, the ribs of juvenile pigs are less calcified and therefore the bones are more flexible and less resistant to stabbing [45,86]. Accordingly, the obtained results using pigs would not be representative for adult humans. However, the organic part of the bones completely burns and leads to a shrinkage of the bone [25,26,28,29,31,35,36,90] and the amount of shrinkage will be higher in juveniles than in adults and the heat modification of cut marks would be also expected to be bigger. If no shrinkage or heat alteration was discovered in this sample, it is very unlikely that adult ribs would show differences.

However, careful research has to be done on this topic, using donated human tissue or a different animal model with similar characteristics. Nevertheless, for the second option, further facts about differences and similarities between model animals and humans have to be collected.

As an additional quality control procedure, all variables were analysed for intra-observer errors, which did not reveal differences. Therefore it can be excluded, that significant results were caused by errors in measurements. Although, nearly 200 cross sections were analysed and provided a good overview on the shapes of these cut marks, overall just 25 cut marks (10 unburnt and 15 burnt) were examined in this study. Morphological cut mark features, such as V-shaped cross sections and striae of the walls were observed. However, little evidence of striation was observed in the whole sample; therefore, whether additional proof for striation was altered by heat or were simply not present remains inconclusive. The burnt specimens could not be analysed before the burning process as they were burnt with flesh.

Furthermore, only the most common knife type in stabbing incidents was used [11,12]. Thus, these results have to be supported by additional research using a higher amount of cut marks as well as different types of knives.

Another reason for a higher degree of variability in the burnt sample might be digital microscopy: Especially for bright samples, like calcined bones, the 3D-reconstruction of the surface can be problematic, because the bone reflects light [71,93], which leads to an irregular reconstructed surface and a needle like appearance. This effect, while obviously affecting the quality of measurements, can be reduced by changing light and contrast conditions, which minimize reflection. However, this procedure is time intensive and exacerbated by the observation that focusing the image on the cut mark floor in oblique or deep cuts can be difficult.

The micro-CT data revealed interesting insights about the procedure of stabbing: Cut marks are not just simple incisions and they do not only harm the bone close to them. The high energy of the impact that spreads through the bone forms multiple cracks in areas next to the cut. If the cut is deep enough this could even lead to a fissure in the floor. However, a correlation between penetration depth and the appearance of fissures could not be detected in unburnt ribs. A reason for this might be that only alterations, which are approximately 15 μm or bigger could be illustrated in this scan and therefore it cannot be completely excluded that these cracks have already been and weakened the structure, which would expand during the burning process. However, more research has to be done to support this hypothesis.

Surprisingly, differences were found between the images rendered with a digital microscope and the micro-CT in nearly all variables. One reason might be the lower resolution of micro-CT (15 μm) in comparison to the digital microscope (5 μm). Additionally, in micro-CT, the partial volume effect (PVE) has a big impact on small structures. The PVE is a diffuse area at the border of two materials between different densities (air and bone), as a pixel is the smallest unit and can only represent one colour (density) at once. Thereby, a mean value of different densities will be chosen [94]. This made it very difficult to set measuring points exactly. Another reason for the significant differences in the obtained results might be the small sample size. Only three very similar cut marks, located next to each other, were scanned with the micro-CT. They might not represent the overall variance of cut marks very well.

In comparison to digital microscopy, micro-CT is an expensive and time consuming method. To receive a sufficient resolution for analyses of cut marks, the field of scan has to be narrowed to approximately 2 cm and only one cut mark can be scanned at once. Thereby, this method is not suited for bigger samples, because the tissue has to be placed close to the X-ray source. Accordingly, it cannot be bigger than approximately 5 cm in diameter. Moreover, one scan would take around three hours and the data size can easily reach 100 GB and more, depending on the resolution. Therefore, expensive software and high-speed computers will be needed to analyse these files.

Digital microscopy in contrast is better suited for cut mark analysis as it is cheaper and quicker and easily provides sufficient resolution. Nevertheless, micro-CT will be an essential method to understand the effects of stabbing.

5. Conclusion

This research provides a new insight into heat alteration of cut marks. Although the literature suggested that bone shrinkage should also affect cut marks, this study revealed that the burning process did not significantly influence cut marks. Most features (depth, width, slope and opening angles, floor radius) can be used for a straight interpretation of used tools and actions of the stabbing process. A transformation was observed in the maximum slope height and floor angles. Moreover, heat-induced changes and possible regularities for both floor angels are not completely investigated yet as no correlations were found in the experimental group for floor angles. Additionally, cracks of the cut mark floor and in areas around cut marks were observed, which clearly demonstrated that stabbing is a complicated process, which is difficult to analyse. Particularly, the mechanical influences on bones need to be analysed in future studies to completely understand the stabbing process. Furthermore, it has to be analysed at which forces these cracks occur to provide a better classification of stabbing forces. The cut mark depth correlates significantly with cracks in the floor. This, however, was only detected in the burnt sample but not at unburnt ribs and should be followed up by further research. A higher resolution of micro-CT images would provide better information about whether these fissures were caused by heat alone or by the combination of stabbing and heat.

Micro-CT and digital microscopy are both suitable methods to analyse cut marks on ribs. However, digital microscopy is cheaper and faster than micro-CT and therefore allows the analysis of larger samples. Due to the fact that both methods provide a different kind of data (digital microscope: surface data; micro-CT: volumes data), it would be beneficial to combine both methods in future analyses.

Overall, whilst this research provides new insights about sharp force trauma on burnt remains as well as a novel quantitative approach to cut mark analyses, further questions about heat alteration and stabbing emerged and, therefore, more research will be needed to better understand these processes.

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