International Journal of Legal Medicine, Volume 136, Issue 1, January 2022, pp. 343-356
DOI: 10.1007/s00414-021-02627-7

Measuring dimensional and morphological heat alterations of dismemberment-related tool marks with an Optical Roughness-meter.

Pilar MATA-TUTOR *: Departamento de Medicina Legal, Psiquiatría y Patología, Laboratorio de Antropología y Odontología Forense, Madrid, Spain (pilmatatutor@gmail.com)

Catherine VILLORIA ROJAS: Departamento de Medicina Legal, Psiquiatría y Patología, Laboratorio de Antropología y Odontología Forense, Madrid, Spain (cvilloria88@gmail.com)

Nicholas MÁRQUEZ-GRANT: Cranfield Forensic Institute, Cranfield University, Defence Academy of the United Kingdom, Shrivenham, UK (n.marquezgrant@cranfield.ac.uk)

Mónica ALVAREZ DE BUERGO BALLESTER: Instituto de Geociencias-IGEO (CSIC, UCM), Madrid, Spain (alvarezm@geo.ucm.es)

Natalia PEREZ EMA: Instituto de Geociencias-IGEO (CSIC, UCM), Madrid, Spain ~~(nperez01@ucm.es~~)

María BENITO SÁNCHEZ: Departamento de Medicina Legal, Psiquiatría y Patología, Laboratorio de Antropología y Odontología Forense, Madrid, Spain (maria.benito@ucm.es)

* **Corresponding author:**

Pilar Mata Tutor (pilmatatutor@gmail.com)

https://orcid.org/0000-0002-6742-9798

Supporting Junior Scientists

The first author (PM) is under 35 years old.

Authors' contributions

Pilar Mata Tutor: Conceptualization, Methodology, Investigation, Software, Formal analysis and interpretation, Visualization, Writing – Original draft, Writing – Editing, Funding acquisition; **Catherine Villoria Rojas:** Methodology, Software, Formal analysis and interpretation, Visualization; **Nicholas Marquéz-Grant:** Supervision, Writing – Editing; **Mónica Álvarez del Buergo Ballester:** Software, Resources; **Natalia Pérez Ema:** Software, Resources; **María Benito Sánchez:** Supervision, Writing – Editing.

Acknowledgments

This experiment adhered to the British Association for Biological Anthropology and Osteoarchaeology guidance on Ethics and Practice and has been funded by their 2020–2021 research grant. We would like to express our gratitude to the members of Petrophysics Laboratory at Geosciences Institute (CSIC, UCM) for the technical assistance provided during the use of the optical Roughness-meter and the electric furnace. We kindly thank Iván Serrano Muñoz for his help and patience during the burning process. Lastly, we thank Daniel García Rubio for his assistance in designing the tables and figures and for providing the samples.

Declarations

Conflicts of interest/Competing interests: None

Funding: This experiment was funded by the British Association for Biological Anthropology and Osteoarchaeology research grant (2020–2021)

Availability of data and material: Not applicable

Code availability: Not applicable

Ethical approval: Not applicable as this experiment adhered to the British Association for Biological Anthropology and Osteoarchaeology guidance on Ethics and Practice

Informed consent: Not applicable

Key words

Forensic anthropology; Sharp force trauma; Fire; Heat-Induced Fractures; Optical Roughness-meter

Highlights

- Fire exposure can distort the signatures of sharp force trauma
- Toolmark’s length decreased in size and roughness increased in a consistent manner
- Serrated knife and machete cutmarks metrics showed no significant variations
- Roughness-meter is a valid non-destructive device that may complement the toolmark analysis

Abstract

This experimental study provides a further understanding of the post-burning nature of sharp force trauma. The main objective is to analyse the distortion that fire may inflict on the length, width, roughness, and floor shape morphology of toolmarks induced by four different implements. To this end, four fresh juvenile pig long bone were cut with a bread knife, a serrated knife, a butcher machete, and a saw. A total of 120 toolmarks were induced and the bone samples were thus burnt in a chamber furnace. The lesions were analysed with a 3D optical surface Roughness-meter before and after the burning process. Afterwards, descriptive statistics and correlation tests (Student's t-test and analysis of variance) were performed. The results show that fire exposure can distort the signatures of sharp force trauma, but they remain recognisable and identifiable. The length decreased in size and the roughness increased in a consistent manner. The width did not vary for the saw, serrated knife, or machete toolmarks, while the bread knife lesions slightly shrunk. The floor shape morphology varied after burning and this change became more noticeable for the three knives. It was also observed that the metrics of the serrated knife and machete cut marks showed no significant variations. Our results demonstrate that there is a variation in the toolmarks characteristics after burning. This distortion is dependent on multiple factors that influence their dimensional and morphological changes, and the preservation of class features is directly reliant upon the weapon employed, the trauma caused and the burning process conditions.

Introduction

Burning is a common method of body disposal [1]. Although fire does not completely destroy a body [2], it contributes to hindering the identification of the victim and to concealing the proof related to the cause and manner of death [3–6]. Fire damages soft tissue and organs and may reduce a full body to bone fragments [7]. Moreover, extreme temperatures can alter, modify and potentially destroy incriminating evidence [8–11], and conceal the victims' identification [12, 13]. Hence, it is essential to analyse the extent of modification that fire induces to pre-burning injuries.

Sharp force trauma is a well-researched and documented category of perimortem trauma. Cut marks induced by a sharp-edged weapon are typically linear striations with a V-shaped cross-section [14–19]. Saw marks are made with the reciprocating "to-and-fro" motion of a saw and leave a square or U-shape in the floor and walls of the bone [14–18, 20–22]. Chopping or hacking trauma is defined as blunt trauma inflicted with a sharp tool using the momentum and physical strength of the offender [23]. It leaves a V- or U-shape depending on the thickness of the blade [24–26].

Likewise, the analysis of the survival and identification of sharp force trauma after burning is well represented in the literature. It has been previously demonstrated that toolmarks are recognisable at macroscopic [5, 9, 10, 27–31] and microscopic [32–38] scales after the burning process. These experiments performed on whole cadavers and disarticulated bones proved that sharp force lesions survive the burning process with a high degree of conservation. Although some heat-induced fractures may be mistaken with pre-burning trauma [31], the latter is recognisable and identifiable [27, 33]. Cut and saw marks remain visible and the kerf walls are sharp and detectable [29, 33]. Researchers have observed that in certain cases, the features are enhanced by thermal alteration [8, 10, 32, 36] and that it is possible to identify the type of saw through analysis based on the striations and morphology of the kerf [5, 35].

As bone undergoes a series of morphological alterations due to thermal damage [39], it seems plausible that these changes might affect the features of the injury. However, the analysis and interpretation of metric changes in toolmarks after burning are scarce and often reach inconclusive results. Experiments have been performed on porcine bones with different weapons, including saws [5, 37], cleavers or hatchets [27, 32] and cooking knives [37, 38]. De Gruchy and Rogers [27] reported that chop marks may decrease in overall size due to burning. Alunni et al. [32] did not report any differences in lesion size before and after carbonisation. Waltenberger and Schutkowski [38] concluded that fire damage did not significantly influence the depth or width of a stab mark, but a transformation was detected in the floor angles due to cracks in the floor. Symes et al. [5] observed that heat alteration did not affect saw marks, with the kerf neither contracting nor expanding in general. Vegh and Rando [37] stated that at 1000 ºC, both the length and width of knife and saw marks varied, but only the length consistently decreased in size.

Therefore, this experiment aims to analyse the distortion that fire may inflict on the dimensions and morphology of toolmarks induced by four different implements: three knives and one saw. It has been proven that the evidence of sharp force trauma can be destroyed during the cremation process and overlooked if not all the fragments are recovered [5, 8–11], but the extent of the dimensional alterations when trauma survives the burning and has been identified as such is not consistent. Moreover, changes in the overall roughness have not been assessed to date and may provide an additional tool to detect differences between weapons. This study provides a further understanding of the post-burning nature of sharp force trauma.

Materials and methods

Bone samples

Four fresh juvenile pig long bones (two femora and two tibiae), weighing 0.7 ± 0.1 kg, were used for this study. The samples were donated to the Laboratorio de Antropología y Odontología Forense (Madrid, Spain) from a local butcher shop in October 2020. Each bone was defleshed immediately prior to the trauma to avoid the influence that protective soft tissue has in the post-burning survival and detection of toolmarks in burnt bones [8–10], and to assure temperature uniformity in all samples [40]. Porcine material was chosen due to it being comparable to a human model for the analysis of cut marks [41, 42] and other forensic anthropology fields [43], and has been used in recent studies as a valid proxy [5, 27, 32, 37, 38]. Long bones were specifically chosen for this experiment to simulate a dismemberment situation in which the aggressor transects the bone via cutting or sawing [17, 44].

Sharp force trauma

A bread knife, a serrated knife, a butcher machete and a saw were chosen for the sharp force trauma experiment due to them being affordable and domestic items used in previous dismemberment cases in Europe, as a sole weapon or in combination with a saw [45–49]. The bread knife and machete were employed in a pilot study in which three donated embalmed cadavers were used to simulate a case in which an attempted dismemberment and burning had occurred, and it was proven that the macroscopic features of the toolmarks were observable and recognisable after the cremation [10, 31]. The characteristics of the weapons can be found in Fig. 1 and Annex 1.

The sharp force trauma experiment consisted of creating a set of toolmarks with different depths and sizes. Each instrument was used on one bone. Thus, 30 lesions per bone were inflicted according to the *controlled* cutting actions detailed in Norman et al. [19], who described it as the action of creating a straight cut with a defined number of strokes. A stroke is considered as one "to-and-fro" motion [19]. Each bone was divided into six sections and cuts were generated progressively with a five-stroke increment: the first section with one stroke; the second with five; the third with ten and so on. Each section included five repetitions (Fig. 2).

A total of 120 toolmarks were manually induced and coded using the following system:

- **F**1BK1.1: The first letter represents the bone (Femur (**F**) or Tibia (**T**));
- F**1**BK1.1: The first number represents the bone number (**1** or **2**);
- F1**BK**1.1: The second letter represents the tool (bread knife (**BK**), saw (**S**), serrated knife (**SK**) or machete (**M**));
- F1BK**1**.1: The second number represents the bone section (**1–6**);
- F1BK1.**1**: The third number represents the toolmark number (**1-30**).

Afterwards, the length of each lesion was measured using a Preciva© digital calliper, with a precision of 0.001 mm.

Roughness-meter

The equipment used for this study was a 3D optical surface Roughness-meter (TRACEiT©, Innowep GMBH), which is a non-destructive, portable, and contactless device that uses white light to analyse surface roughness parameters and 3D surface tomography. This device was chosen to acquire detailed images of the toolmarks before and after the burning process. The parameter selected to measure the surface roughness was the mean roughness depth (Rz) according to DIN EN ISO 4287 standards [50]. Rz is the arithmetic mean value of the single roughness depths, the vertical distance between the highest peak and the deepest point [51].

Each lesion was measured in three or two areas, depending on the length of the lesion, to analyse as much of the surrounding surface as possible. The first measurement was taken in the upper part of the toolmark, at the up-most distal part. The second was taken in the middle, at the deepest area. The third was taken at the end of the toolmark, at the proximal part. Each measurement generated one three-dimensional (3D) roughness topographic map of 500×500 μm, eight black and white images and a roughness value for the x and y axes. The Rz value for each toolmark was obtained by calculating the arithmetic mean of Rz for each surface measurement. The maximum width of each lesion and the floor shape was assessed using the TRACEiT© software for Windows 7 OS.

The generated 3D roughness topographic maps were processed using Gwyddion© v 2.43 for Windows 10 OS, a modular program for scanning probe microscopy data visualisation and analysis. The topographic maps were resized and coloured using a colour code for each sample: *Blend2* (F1BK); *Cold* (F2S); *Gwyddion.net* (T1SK) and *Sky* (T2M). These data were used to analyse the floor shape of each toolmark.

Burning process

A laboratory chamber furnace (Carbolite© CWF 1200) with an 1100 °C maximum operating temperature and adjustable duration controls was used for the burning process. The samples were placed inside the furnace at 39 ºC and heated up until the temperature reached 850 °C. Following the methodology of previous authors [28, 37], they were left at 850 °C for 30 min to achieve complete calcination. The cremation lasted ~5 h considering the total heat exposure. However, the temperature was only over 200 °C for 195 min, which is the minimum temperature reported for thermal changes to occur [28, 39]. After the procedure finished, the bones were left to cool overnight. The burning process is depicted in Fig. 3. The length, width, roughness, and floor shape of each toolmark were calculated after cooling. In total, before and after the burning, more than 600 measurements were taken.

Statistical analysis

All data obtained were recorded in a database and processed using SPSS© software v 25.0 for Windows 10 OS (SPSS Inc., Chicago, IL). A descriptive morphological analysis was performed for the floor shape of each toolmark. Descriptive statistics were performed to obtain the means, standard deviation and ranges of the lesion length, width and roughness. Afterwards, a Kolmogorov–Smirnov normality test was conducted and it was concluded that all the variables followed a normal distribution ($p > 0.05$). To analyse the mean differences between the length, width and roughness before and after the burning process, the Student's *t*-test for independent samples was employed by studying "pre-burning" and "post-burning" variables separately and assessing the degree of their relationship. Univariate analysis of variance (ANOVA) was used to assess the relationship between the dimensions and the specific tools. Bonferroni tests were used to determine if there were significant differences among the categories determined by ANOVA. Four groups corresponding to each tool were thus established (bread knife, saw, serrated knife and machete). The statistical tests were considered significant if $p \leq 0.05$.

Results

Metrics

Table 1 lists the measurements taken before and after the burning process and the number of heat-induced fractures that damaged the toolmarks in each bone section. The bread knife inflicted the longest cut marks, while the saw generated the widest. This pattern was preserved after the burning. The average roughness before cremation was consistent for all tools but varied substantially after burning.

It can be observed in the Supplementary material (Annex 2) and Table 1 that the two femurs suffered intense damage from heat-induced fractures, which ruptured or modified 90.00% of the cut marks for Femur_1 (F1BK) and 83.33% of the saw marks for Femur_2 (F2S).

Roughness-meter

Figures 4–7 present the Optical Roughness-meter results for each tool. The average roughness increased after the burning process and some features were more visible afterwards due to the blackish colour surrounding the toolmark. The overall morphology and floor shape of the cutmarks changed and this variation was more noticeable in the lesions induced by the bread knife. The bread knife cut marks exhibited irregular shapes, the serrated knife sharper walls and the machete progressively rounder floors. The saw marks preserved a wide U-shape.

Student's t-test for mean comparisons

Table 2 presents the descriptive statistics and the Student's t-test results. A high significant result of $p \leq 0.001$ was observed at all levels of the Student's t-test between the mean length and the main roughness of the toolmarks after the burning process. The length decreased after fire damage, while the roughness increased substantially. The mean width only showed a significant result of $p \leq 0.05$ in the cuts induced with the bread knife. Annexes 3–5 present the distribution of length, width and roughness by tool and burning process. The black braces represent the Student's t-test p value for mean comparisons.

ANOVA for tool differences

Table 3 presents the ANOVA results. The ANOVA generated a p value of ≤ 0.05, indicating a significant difference between the tools and length, width and roughness, correlations that frequently varied after the burning process. Bonferroni tests for the tool groups revealed that the serrated knife and machete cut marks had no significant differences in any measurements. The saw metrics were different to the other tools, except for the pre-burning roughness, which showed no significant variations between the bread knife and saw and saw and machete. Annexes 3–5 present the distribution of length, width and roughness by tool and burning process. The pink and blue braces show the post-hoc results for multiple comparisons in pre- and post-burning bones, respectively.

Discussion

Our experiment aimed to gain a further understanding of the post-burning behaviour of toolmarks made with different serrated and non-serrated implements. After burning, all lesions remained visible and identifiable and exhibited morphological features consistent with sharp force trauma [31], although both femurs suffered intense thermal-induced damage across the main shaft of the bone, breaking in half more than 80% of the toolmarks. This result is consistent with previous findings [8–11] that showed the susceptibility of peri-mortem trauma in being destroyed by heat damage (Fig. 8). Several studies have proved that bone shrinks during the burning process [3, 4, 7, 39, 52, 53] and this size reduction has been likewise observed in the length results for toolmarks, in agreement with previous studies [27, 37]. However, no major alteration was detected in width for saws, in accordance with Symes et al. [5], or for serrated knife and machete, concurring with Waltenberger and Schutkowski [38].

Length

The results obtained for the toolmark lengths expand upon former studies. Waltenberger and Schutkowski [38] did not evaluate statistically the length of the stab marks, as it was dependent on the location at which the knife stabbed the porcine rib. Symes et al. [5] did not report changes to the length of the saw marks. De Gruchy and Rogers [27] observed that the chop marks induced with a cleaver and burnt in an outdoor fire for ~3 h were largely unaffected by burning, but the shrinkage slightly reduced their size. Although this observation was not measured in their experiment, it agrees with our result for the length of each toolmark decreasing consistently ($p \leq 0.001$) (Annex 3). Vegh and Rando [37] reported a steady contraction of lesions that were burnt at 1000 ºC for 20 min. At 800 ºC, only the wood saw exhibited a 10% shrinkage coefficient, although the kitchen knife and hack saw toolmarks also marginally decreased in size. Our results agree with their observations, with the saw marks being the most affected weapon regarding length ($p \leq 0.001$). This noticeable shrinkage may be clarified due to the extreme fragmentation caused by longitudinal fractures that broke the femur shaft.

However, Alunni et al. [32] reported no significant variations. These contradictory results can be explained due to the different methodology and the total heat exposure time. While in the present study and that of de Gruchy and Rogers [27], the samples were burnt for long periods of time (> 3 h), Alunni et al. [32] and Vegh and Rando [37] removed the bones after < 30 min of fire exposure; thus observing no shrinkage [32] and a minor contraction [37].

Width

Regarding width, no significant variation was found in size before and after the burning process for the saw, serrated knife and machete toolmarks ($p > 0.05$) (Annex 4). These results also confirm previous findings. Symes et al. [5] reported that extreme heat alteration does not affect kerf characteristics and therefore conserves their diagnostic value. We observed that while the saw marks substantially decreased in length due to thermal damage, their width did not alter, and their class characteristics were preserved. Moreover, Waltenberger and Schutkowski [38] reported that burning did not significantly influence the stab dimensions with a non-serrated knife. Their conclusions agree with our results for the serrated knife and machete, in that the width of the cut marks did not fluctuate and lesions were well-preserved after the burning process.

It can be noticed that machete lesions appear slightly wider after the burning process. Vegh and Rando [37] observed in their experimental study that breakage induced to the bone walls during the cutting motion is smoothed over during fire damage, which exposes the floor easily at a microscopic scale. This phenomenon was not detected for the other implements and agrees with the macroscopic observation. Severe wall damage was induced by the machete, even when performing a cutting motion rather than chopping trauma [25]. A marginal shrinkage in cut marks made with the bread knife was detected ($p \leq 0.05$). This outcome agrees with the observations made by Vegh and Rando [37], where kitchen knife cut marks shrank both at 800 and 1000 ºC. It has been previously discussed that trauma induced by different weapons may have distinct post-burning survival [10] and while this shrinkage in width differs from the findings of

Waltenberger and Schutkowski [38], it suggests that toolmark dimensions may also behave differently during fire damage depending on the implement used.

Roughness

Roughness profile analysis has been used in other scientific fields, including odontology [54], geology [50, 51] and archaeology [55]. The aim is to compare the changes before and after performing a chemical or taphonomic treatment. To date, no studies have attempted to apply surface roughness as a forensic tool to analyse the morphological variations of lesions induced by different weapons before and after burning. Thus, it is not possible to draw a comparison with previous experiments. Nevertheless, the results obtained are in accordance with the morphological heat-induced changes that bones undergo when submitted to fire damage.

Once a bone is directly exposed to heat, it goes through dehydration, decomposition, inversion and fusion [3, 4, 39]. Thompson [4] reported recrystallisation from 500 ºC, which affects bone surface and porosity. Our results showed that the roughness increased greatly in a consistent manner ($p \leq 0.001$) (Annex 5). Hence, it was demonstrated that these heat-induced changes increase the surface irregularity and coarseness that is observable microscopically and can be measured with an Optical Roughness-meter (Figs. 4–7). All the surface of each toolmark was more irregular after burning. In particular, it was observed that the roughness of the serrated knife and machete cut marks abruptly increased (Figs. 6 and 7). Therefore, these differences found in metrics might be an additional forensic tool in future studies to help identify the specific weapon that caused a lesion.

Floor shape

The overall morphology of the toolmarks agreed with the literature for both intact [12–24] and burnt bones [5, 8–10, 25–36]. The saw left a wide U-shape on the bone surface that was maintained after fire damage. Contrary to Marciniak [35] and Symes et al. [5], who stated that certain portions of bone retained evidence of a particular tool, the kerfs exhibited only class features. The preservation of the identifying striae depends on the “to-and-fro” action and the type of saw used [17, 18, 20–22], and while Marciniak [35] and Symes et al. [5] burnt the samples at < 500 ºC, the present bones were burnt at a maximum of 850 ºC and the lesions did not transect the bone. Thus, higher temperatures and different manners of inducing the injury have the potential to obliterate identifying patterns on saw marks. The knives exhibited a narrow V-shaped cross section that was especially obvious on superficial lesions. These toolmarks were recognisable and identifiable macroscopically as induced by a knife, presenting well-preserved class characteristics that were even enhanced after the burning process, in agreement with previous authors [8, 10, 32, 36]. A blackish colour could be detected surrounding these lesions (Fig. 8). However, the differentiation between weapons based on microscopic floor morphology was challenging.

While the machete and serrated knife presented a visible V-shape in all bone sections after burning and saw a characteristic U-shape, the bread knife created erratic and saw-like lesions with W-, U- and wide V-shapes. The unpredictable pattern was accentuated after burning. Porta et al. [56] stated that serrated knives sometimes behaved in an arbitrary way, inducing strange shapes and morphologies that obscure the identification of a particular tool. This could be due to the sawing motion performed with a knife with separated teeth (Fig. 1), which cuts through by compression in the direction in which the blade is moving [16, 23]. This same bread knife generated cut marks in human cadavers that were susceptible to be confused with a fine saw after cremation [10]. Thus, the obtained results coincided with observations made for intact [56] and burnt human bone [10].

Correlation between tools

Cut marks induced by the three knives were distinguishable from saw marks due to their different metric values and floor shape, in agreement with the literature [14, 17, 18]. Saw kerfs conserved their identifying characteristics, both macroscopically and microscopically, and were recognisable from the cut marks of the knives. Additionally, the blackish shade observed in cut marks after burning was not present in saw marks. Regarding width, the Bonferroni test revealed no significant differences between the three knives. With respect to roughness, no significant differences were found between the bread knife and the serrated knife. These results are reasonable based on the characteristics of the weapons. The bread and serrated knifes both had indented blades while the machete did not; hence, some differences were expected [57, 58]. Although the shapes of the bread knife cut marks can behave in erratic and inconclusive ways [10, 56], the dimensional changes were logical and similar to other knives, which assisted in their differentiation from a saw mark.

The serrated knife and machete metrics and morphology were almost indistinguishable from one another before and after burning. The machete cut marks were slightly rounded after the burning process (Fig. 7), while the shape of the serrated knife lesions was sharper upon microscopical observation of the 3D topography map (Fig. 6). However, both sets of cut marks preserved a visible V-shape with sharp edges at macroscopic and microscopic scales. The Bonferroni test showed that no statistical difference was found in any of the measurements ($p > 0.05$). In these cases, an additional examination of striations on the superficial cut marks could be of use to distinguish between these two implements [19, 57], since dimensional changes were revealed to have no evidentiary value. However, in agreement with previous researchers [32, 34], no striations were detected within toolmarks neither in fresh nor burned bones in this experiment. Porta et al. [56] observed that serrated knives sometimes behaved as non-serrated blades, due to the cutting motion erasing the striations, and their conclusion might explain the results obtained. Thus, more studies are required to elaborate on the metric and morphological differences between serrated and non-serrated knives after burning.

The results of the present experiment showed that there is a variation in sharp force trauma characteristics after burning. This distortion that fire inflicts on a toolmark is dependent on multiple factors that influence their dimensional and morphological changes. The preservation of class features is directly reliant on the weapon employed, the trauma caused and the burning process conditions.

Conclusions

This experimental study analysed the post-burning dimensional and morphological changes of toolmarks related to dismemberment using an Optical Roughness-meter. It is acknowledged that porcine defleshed material burnt in an electric furnace was selected rather than whole cadavers in an open pyre, which might have influenced the degree of survival, fragmentation, and features characteristics. Further experimentation using fleshed bones is encouraged to evaluate the behaviour of these morphological and dimensional features under different conditions. Moreover, only one researcher performed the cut and saw marks (PM), which could affect the toolmarks' features if a person of different musculature were to repeat this experiment. Nevertheless, the results are consistent with previous studies and provide valuable information for the forensic anthropology field.

The results showed that fire exposure can distort the signatures of sharp force trauma, but they are still recognisable and identifiable even after intense heat for long periods of time. The length decreased in size and the roughness significantly increased in a consistent manner. The width did not vary for the saw, serrated knife, and machete toolmarks, while the bread knife lesions slightly shrank. The floor shape morphology varied after burning and this change was more noticeable in the three knives. The saw kerfs maintained a wide U-shape, the serrated knife and machete cut marks exhibited a sharp V-shape and the bread knife created erratic shapes that were even more irregular after burning. It was also observed that the serrated knife and machete cut mark metrics showed no significant variations. Additional experiments should evaluate if the differences found are sufficient to discriminate between tools. Moreover, it has been proven that the Roughness-meter is a valid portable, straightforward, and non-destructive device that may complement the toolmark analysis without damaging the sample, providing a detailed surface analysis.

The degree of heat-induced alterations in sharp force trauma within a forensic context involving dismemberment and limb mutilation depends on multiple factors, such as the weapon employed, how the lesions are inflicted, the presence of protective soft tissue and the burning process conditions, including time exposure and temperature. Therefore, experimental studies of toolmarks induced by various implements under different conditions are recommended to discover more variables that affect the dimensions of trauma in burnt bones and gain a further understanding of its post-burning behaviour.

List of Tables

List of Figures

Fig. 5. **Femur cut with a saw** (F2S). This figure depicts the morphology and roughness of one randomly selected saw mark of each femur section (1–6) before and after the burning process. The colour bar represents the depth of each saw mark. It was noticed that superficial injuries had a W-shape, whereas deep cuts exhibited a U- or wide V-shape. After burning, the saw marks showed greater roughness overall but preserved the floor shape. All selected toolmarks were broken in half by longitudinal heat-induced fractures, except for F2S6.26.

Fig. 6. **Tibia cut with a serrated knife** (T1SK). This figure depicts the morphology and roughness of one randomly selected cut mark of each tibia section (1–6) before and after the burning process. The colour bar represents the depth of each cut mark. Overall, all cuts induced with the serrated knife exhibited a V-shape and were narrower on superficial marks. After burning, the toolmarks showed greater roughness and sharper walls. T1SK2.8-9 were damaged by a longitudinal fracture.

Fig. 7. **Tibia cut with a machete** (T2M). This figure depicts the morphology and roughness of one randomly selected cut mark of each tibia section (1–6) before and after the burning process. The colour bar represents the depth of each cut mark. Cuts induced with the machete exhibited a V-shape, with the floor becoming progressively rounded as the trauma deepened. After burning, the toolmarks showed greater roughness and even rounder floor shapes. T1SK2.10 and T2M5.23 were broken by heat-induced fractures.

Fig. 8. **Heat-induced changes observed after the burning process**. The first image shows a longitudinal fracture that transects two pre-existing cuts (T1SK2.7-8). The second depicts a transverse fracture that breaks in half the pre-existing cut (F1BK2.8). The third shows a widened cut mark (T1SK3.11). The fourth points to two unintentional false-start marks that had been enhanced and are more visible after burning (T2M4.20).

Supplementary material

Annex 1. **Tools.** Four instruments were used for the experiment. From left to right: Bread knife (BK); Saw (S); Serrated knife (SK) and Machete (M).

Annex 2. **Bones before and after the burning process.** The samples were placed in the following order from back to front: Tibia_2 (T2M); Tibia_1 (T1SK); Femur_2 (F2S) and Femur_1 (F1BK). The left image shows the bones before the experiment and the right image illustrates the bones during the cooling process.

Annex 3. **Distribution of length by tool and burning process**. The black braces represent the Student's t-test p value for mean comparisons. The pink braces represent the post-hoc results for multiple comparisons in pre-burning bones. The blue braces represent the post-hoc results for multiple comparisons in post-burning bones. *: $p \leq 0.05$; **: $p \leq 0.01$; ***: $p \leq 0.001$.

Annex 4. **Distribution of width by tool and burning process**. The black braces represent the Student's t-test p value for mean comparisons. The pink braces represent the post-hoc results for multiple comparisons in pre-burning bones. The blue braces represent the post-hoc results for multiple comparisons in post-burning bones. *: $p \leq 0.05$; **: $p \leq 0.01$; ***: $p \leq 0.001$.

Annex 5. **Distribution of roughness by tool and burning process**. The black braces represent the Student's t-test p value for mean comparisons. The pink braces represent the post-hoc results for multiple comparisons in pre-burning bones. The blue braces represent the post-hoc results for multiple comparisons in post-burning bones. *: $p \leq 0.05$; **: $p \leq 0.01$; ***: $p \leq 0.001$.

References

1. Alunni V, Grevin G, Buchet L, Quatrehomme G (2014) Forensic aspect of cremations on wooden pyre. Forensic Sci Int 241:167–172. https://doi.org/10.1016/j.forsciint.2014.05.023
2. Bohnert M, Rost T, Pollak S (1998) The degree of destruction of human bodies in relation to the duration of the fire. Forensic Sci Int 95:11–21. https://doi.org/10.1016/S0379-0738(98)00076-0
3. Mayne Correia P (1996) Fire Modification of Bone. In: Haglund WD, Sorg MH (eds) Forensic Taphonomy: The Postmortem Fate of Human Remains. CRC Press
4. Thompson TJU (2004) Recent advances in the study of burned bone and their implications for forensic anthropology. Forensic Sci Int 146:S203–S205. https://doi.org/10.1016/j.forsciint.2004.09.063
5. Symes SA, Dirkmaat DC, Ousley S, et al (2012) Recovery and Interpretation of Burned Human Remains. BiblioGov 236
6. Fairgrieve SI (2008) Forensic cremation: Recovery and analysis. CRC Press, Boca Raton, Florida
7. Ubelaker DH (2009) The forensic evaluation of burned skeletal remains: A synthesis. Forensic Sci Int 183:1–5. https://doi.org/10.1016/j.forsciint.2008.09.019
8. Emanovsky P, Hefner JT, Dirkmaat DC (2002) Can Sharp Force Trauma To Bone Be Recognized After Fire Modification? An Experiment Using Odocoileus virginianus (White-Tailed Deer) Ribs. Proc from Annu Meet Am Acad Forensic Sci 8:214–215
9. Koch S, Lambert J (2017) Detection of Skeletal Trauma on Whole Pigs Subjected to a Fire Environment. J Anthropol Reports 02:1–7. https://doi.org/10.35248/2684-1304.17.2.113
10. Mata Tutor P, Márquez-Grant N, Villoria Rojas C, et al (2020) Through fire and flames: post-burning survival and detection of dismemberment-related toolmarks in cremated cadavers. Int J Legal Med 1–15. https://doi.org/10.1007/s00414-020-02447-1
11. Franceschetti L, Mazzucchi A, Magli F, et al (2021) Are cranial peri-mortem fractures identifiable in cremated remains? A study on 38 known cases. Leg Med 49:101850.

https://doi.org/10.1016/j.legalmed.2021.101850

12. Ochôa Rodrigues C, Ferreira MT, Matos V, Gonçalves D (2020) “Sex change” in skeletal remains: Assessing how heat-induced changes interfere with sex estimation. Sci Justice 0–1. https://doi.org/10.1016/j.scijus.2020.09.007
13. Gonçalves D, Thompson TJU, Cunha E (2013) Osteometric sex determination of burned human skeletal remains. J Forensic Leg Med 20:906–911. https://doi.org/10.1016/j.jflm.2013.07.003
14. Love JC (2019) Sharp force trauma analysis in bone and cartilage: A literature review. Forensic Sci Int 299:119–127. https://doi.org/10.1016/j.forsciint.2019.03.035
15. Byers SN (2016) Sharp and Miscellaneous Trauma. In: Byers SN (ed) Introduction to forensic anthropology, 4th ed. Taylor & Francis, pp 320–335
16. Symes SA, Williams J, Murray E, et al (2001) Taphonomic Context of Sharp-Force Trauma in Suspected Cases of Human Mutilation and Dismemberment. In: Haglund WD, Sorg MH (eds) Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives. CRC Press, Boca Raton, Fla, pp 403–434
17. Symes SA, Chapman EN, Rainwater CW, et al (2010) Knife and Saw Toolmark Analysis in Bone: A Manual Designed for the Examination of Criminal Mutilation and Dismemberment. Pennsylvania Mercyhurst Coll 142
18. Kimmerle EH, Baraybar JP (2008) Sharp Force Trauma. In: Taylor & Francis Inc (ed) Skeletal trauma: identification of injuries resulting from human rights abuse and armed conflict. CRC Press, Boca Raton, pp 263–314
19. Norman DG, Watson DG, Burnett B, et al (2018) The cutting edge — Micro-CT for quantitative toolmark analysis of sharp force trauma to bone. Forensic Sci Int 283:156–172. https://doi.org/10.1016/j.forsciint.2017.12.039
20. Ross AH, Radisch D (2019) Toolmark Identification on Bone. In: Dismemberments. Elsevier, pp 165–182

21. Saville PA, Hainsworth S V., Rutty GN (2007) Cutting crime: the analysis of the “uniqueness” of saw marks on bone. Int J Legal Med 121:349–357. https://doi.org/10.1007/s00414-006-0120-z

22. Love JC, Derrick SM, Wiersema JM, Peters C (2015) Microscopic Saw Mark Analysis: An Empirical Approach. J Forensic Sci 60:S21–S26. https://doi.org/10.1111/1556-4029.12650

23. Sanabria-Medina C, Osorio Restrepo H (2019) Dismemberment of Victims in Colombia. In: Dismemberments. Elsevier, pp 7–41

24. Alunni-Perret V, Borg C, Laugier J-P, et al (2010) Scanning Electron Microscopy Analysis of Experimental Bone Hacking Trauma of the Mandible. Am J Forensic Med Pathol 31:326–329. https://doi.org/10.1097/PAF.0b013e3181e2ed0b

25. Humphrey JH, Hutchinson DL (2001) Microscopic Characteristics of Hacking Trauma. J Forensic Sci 46:228–233. https://doi.org/10.1520/JFS14955J

26. McCardle P, Stojanovski E (2018) Identifying Differences Between Cut Marks Made on Bone by a Machete and Katana: A Pilot Study. J Forensic Sci 63:1813–1818. https://doi.org/10.1111/1556-4029.13754

27. de Gruchy S, Rogers TL (2002) Identifying Chop Marks on Cremated Bone: A Preliminary Study. J Forensic Sci 47:15506J. https://doi.org/10.1520/JFS15506J

28. Macoveciuc I, Márquez-Grant N, Horsfall I, Zioupos P (2017) Sharp and blunt force trauma concealment by thermal alteration in homicides: An in-vitro experiment for methodology and protocol development in forensic anthropological analysis of burnt bones. Forensic Sci Int 275:260–271. https://doi.org/10.1016/j.forsciint.2017.03.014

29. Pope EJ, Smith OC (2004) Identification of Traumatic Injury in Burned Cranial Bone: An Experimental Approach. J Forensic Sci 49:1–10. https://doi.org/10.1520/JFS2003286

30. Poppa P, Porta D, Gibelli D, et al (2011) Detection of Blunt, Sharp Force and Gunshot Lesions on Burnt Remains. Am J Forensic Med Pathol 32:275–279. https://doi.org/10.1097/PAF.0b013e3182198761

31. Mata Tutor P, Benito Sánchez M, Villoria Rojas C, et al (2021) Cut or burnt? – Categorizing morphological characteristics of heat-induced fractures and sharp force trauma. Leg Med 50:101868. https://doi.org/10.1016/j.legalmed.2021.101868

32. Alunni V, Nogueira L, Quatrehomme G (2018) Macroscopic and stereomicroscopic comparison of hacking trauma of bones before and after carbonization. Int J Legal Med 132:643–648. https://doi.org/10.1007/s00414-017-1649-8

33. Herrmann NP, Bennett JL (1999) The Differentiation of Traumatic and Heat-Related Fractures in Burned Bone. J Forensic Sci 44:14495J. https://doi.org/10.1520/JFS14495J

34. Kooi RJ, Fairgrieve SI (2013) SEM and Stereomicroscopic Analysis of Cut Marks in Fresh and Burned Bone. J Forensic Sci 58:452–458. https://doi.org/10.1111/1556-4029.12050

35. Marciniak S-M (2009) A Preliminary Assessment of the Identification of Saw Marks on Burned Bone. J Forensic Sci 54:779–785. https://doi.org/10.1111/j.1556-4029.2009.01044.x

36. Robbins SC, Fairgrieve SI, Oost TS (2015) Interpreting the Effects of Burning on Pre-incineration Saw Marks in Bone. J Forensic Sci 60:S182–S187. https://doi.org/10.1111/1556-4029.12580

37. Vegh EI, Rando C (2018) Effects of Heat as a Taphonomic Agent on Kerf Dimensions. Archaeological Environmental Forensic Sciences 1:105–118. https://doi.org/10.1558/aefs.35927

38. Waltenberger L, Schutkowski H (2017) Effects of heat on cut mark characteristics. Forensic Sci Int 271:49–58. https://doi.org/10.1016/j.forsciint.2016.12.018

39. Thompson TJU (2005) Heat-induced Dimensional Changes in Bone and their Consequences for Forensic Anthropology. J Forensic Sci 50:1–8. https://doi.org/10.1520/JFS2004297

40. Ellingham STD, Thompson TJU, Islam M, Taylor G (2015) Estimating temperature exposure of burnt bone — A methodological review. Sci Justice 55:181–188. https://doi.org/10.1016/j.scijus.2014.12.002

41. Bonney H, Goodman A (2020) Validity of the use of porcine bone in forensic cut mark studies. J Forensic Sci 1556-4029.14599. https://doi.org/10.1111/1556-4029.14599

42. Pearce A, Richards R, Milz S, et al (2007) Animal models for implant biomaterial research in bone: A review. Eur Cells Mater 13:1–10. https://doi.org/10.22203/eCM.v013a01

43. Matuszewski S, Hall MJR, Moreau G, et al (2020) Pigs vs people: the use of pigs as analogues for humans in forensic entomology and taphonomy research. Int J Legal Med 134:793–810. https://doi.org/10.1007/s00414-019-02074-5

44. Rainwater CW (2015) Three modes of dismemberment: disarticulation around the joints, transection of bone via chopping, and transection of bone via sawing. In: Skeletal trauma analysis. John Wiley & Sons, Ltd, Chichester, UK, pp 222–245

45. Konopka T, Strona M, Bolechała F, Kunz J (2007) Corpse dismemberment in the material collected by the Department of Forensic Medicine, Cracow, Poland. Leg Med 9:1–13. https://doi.org/10.1016/j.legalmed.2006.08.008

46. Mata Tutor P, Villoria Rojas C (2020) Vayamos por partes - Desmembramiento y mutilación en España en los últimos 10 años. V Anuario Internacional de Criminología y Ciencias Forenses, SECCIF 5:165–185

47. Wilke-Schalhorst N, Schröder AS, Püschel K, Edler C (2019) Criminal corpse dismemberment in Hamburg, Germany from 1959 to 2016. Forensic Sci Int 300:145–150. https://doi.org/10.1016/j.forsciint.2019.04.038

48. Black S, Rutty G, Hainsworth S, Thomson G (2017) Introduction to criminal human dismemberment. In: Black S, Rutty G, Hainsworth S, Thomson G (eds) Criminal Dismemberments, 1st ed. CRC Press, Boca Raton, pp 1–6

49. Mata Tutor P, Márquez-Grant N, Villoria Rojas C, et al (Under review) Cadaver dismemberment and posterior destructive alteration as a method of body disposal in Spanish forensic cases. J Forensic Leg Med

50. Vazquez-Calvo C, Alvarez de Buergo M, Fort R, Varas-Muriel MJ (2012) The measurement of surface roughness to determine the suitability of different methods for stone cleaning. J Geophys

Eng 9:S108–S117. https://doi.org/10.1088/1742-2132/9/4/S108

51. Miller AZ, Rogerio-Candelera MA, Dionísio A, et al (2012) Evaluación de la influencia de la rugosidad superficial sobre la colonización epilítica de calizas mediante técnicas sin contacto. Mater Construcción 62:411–424. https://doi.org/10.3989/mc.2012.64410

52. Ellingham S, A. Sandholzer M (2020) Determining Volumetric Shrinkage Trends of Burnt Bone Using Micro- CT. J Forensic Sci 65:196–199. https://doi.org/10.1111/1556-4029.14150

53. Vassalo AR, Mamede AP, Ferreira MT, et al (2019) The G-force awakens: the influence of gravity in bone heat-induced warping and its implications for the estimation of the pre-burning condition of human remains. Aust J Forensic Sci 51:201–208. https://doi.org/10.1080/00450618.2017.1340521

54. Báez Calderón A (2018) Aplicación de peróxido de hidrógeno al 40% con o sin activadores y su efecto sobre esmalte, estudio in vitro al rugosímetro. Universidad Central del Ecuador (Bachelor Thesis)

55. Casanova X, Roldán M, Subirà ME (2020) Analysis of cut marks on ancient human remains using confocal profilometer. J Hist Archaeol Anthropol Sci 5:18–26. https://doi.org/10.15406/jhaas.2020.05.00213

56. Porta D, Amadasi A, Cappella A, et al (2016) Dismemberment and disarticulation: A forensic anthropological approach. J Forensic Leg Med 38:50–57. https://doi.org/10.1016/j.jflm.2015.11.016

57. Thompson TJU, Inglis J (2009) Differentiation of serrated and non-serrated blades from stab marks in bone. Int J Legal Med 123:129–135. https://doi.org/10.1007/s00414-008-0275-x

58. Stanley SA, Hainsworth S V., Rutty GN (2018) How taphonomic alteration affects the detection and imaging of striations in stab wounds. Int J Legal Med 132:463–475. https://doi.org/10.1007/s00414-017-1715-2

Fig 1

Click here to access/download;Figure;Fig 1 - Tools.png

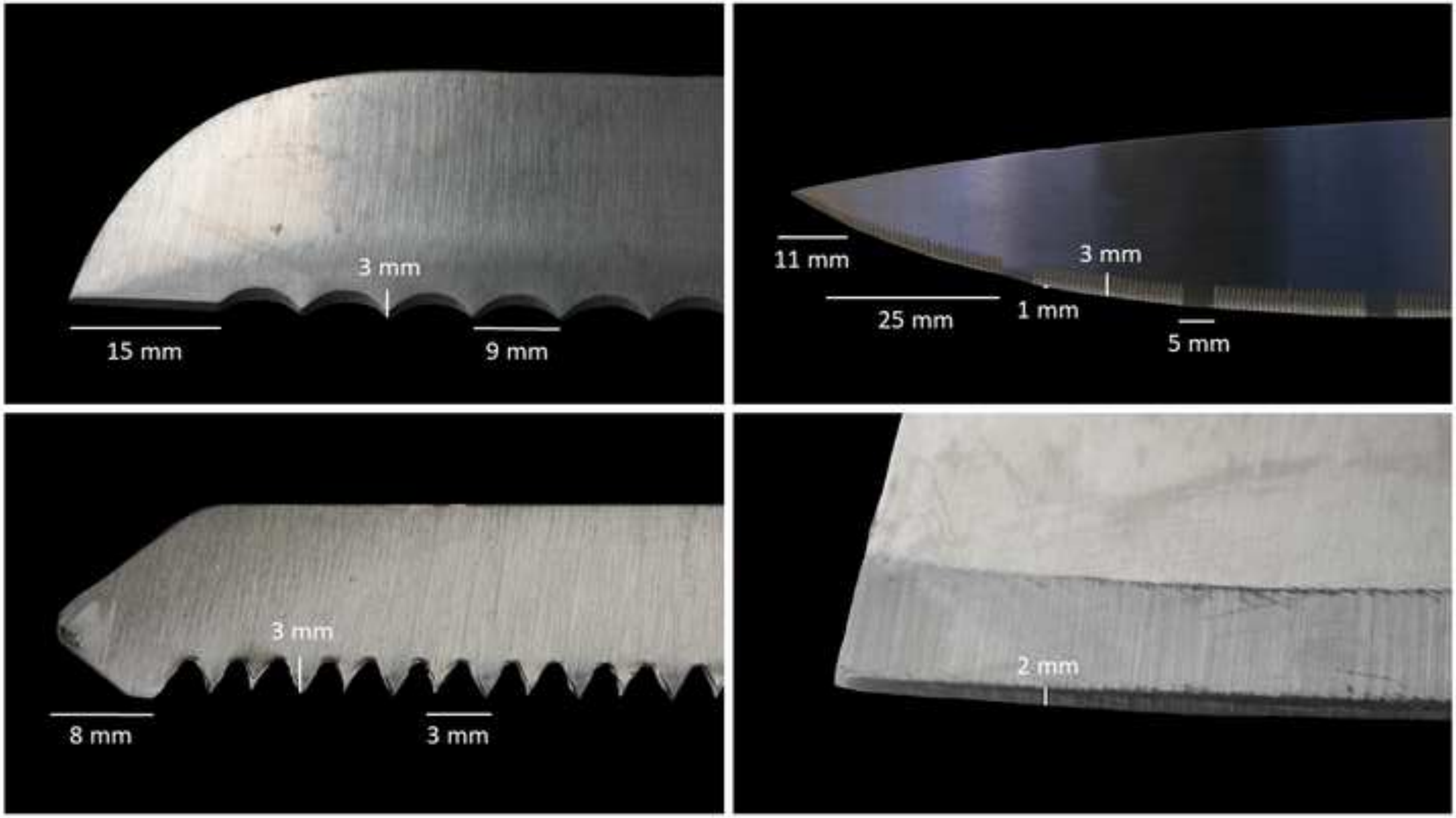
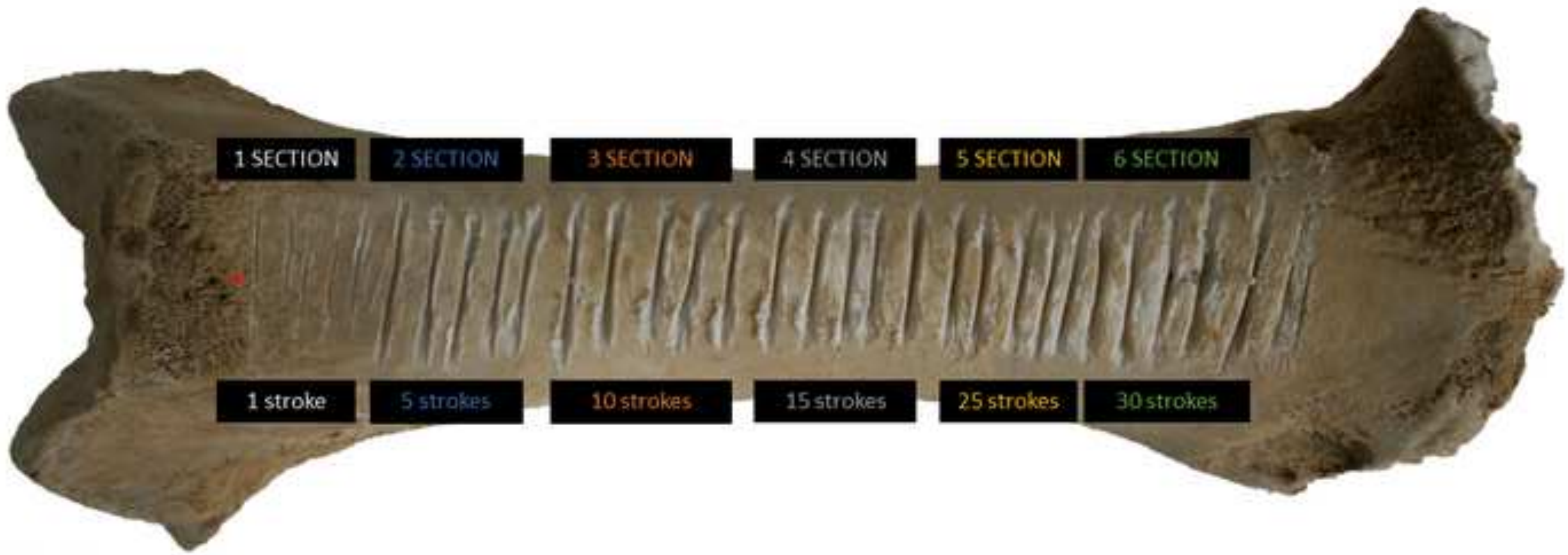


Fig 2

Click here to access/download;Figure;Fig 2 - Experiment design.png



F1BK1.1 *

F1: Femur 1

BK: Bread knife

1: First section

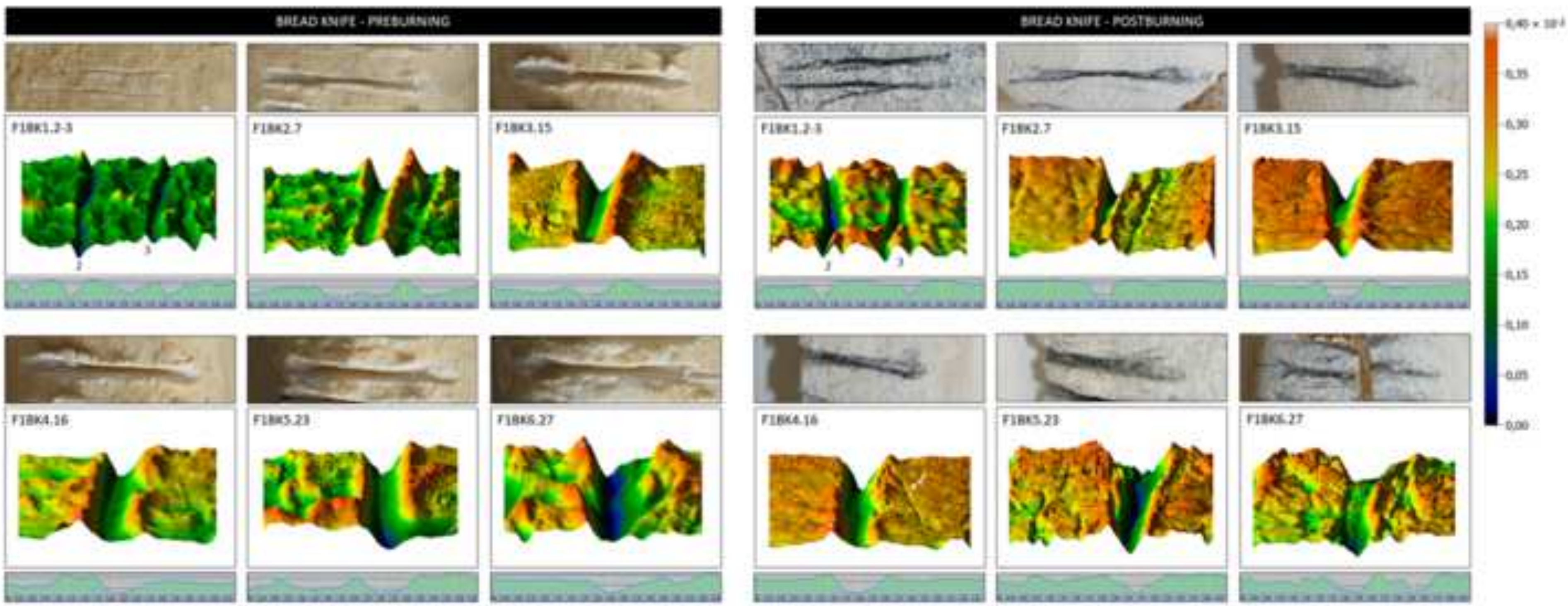
.1: First toolmark

Fig 3


Min 1 - 39 °C
Min 15 - 350 °C
Min 27 - 560 °C
Min 50 - 773 °C
Min 60 - 850 °C
Min 78 - 850 °C
Min 123 - 640 °C
Min 186 - 382 °C
Min 247 - 111 °C

Fig 4

Click here to access/download;Figure;Fig 4 - Bead knife.png



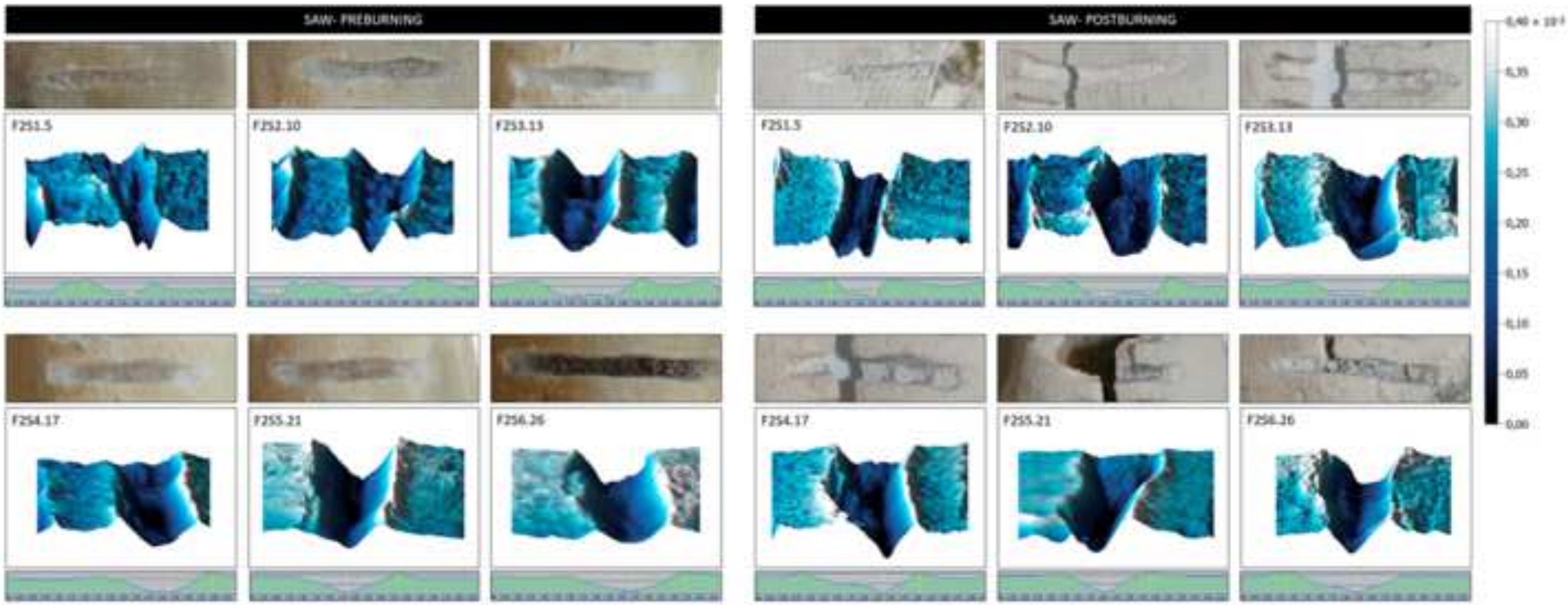

SAW- PREBURNING
SAW- POSTBURNING
F2S1.5
F2S2.10
F2S3.13
F2S4.17
F2S5.21
F2S6.26

Fig 6

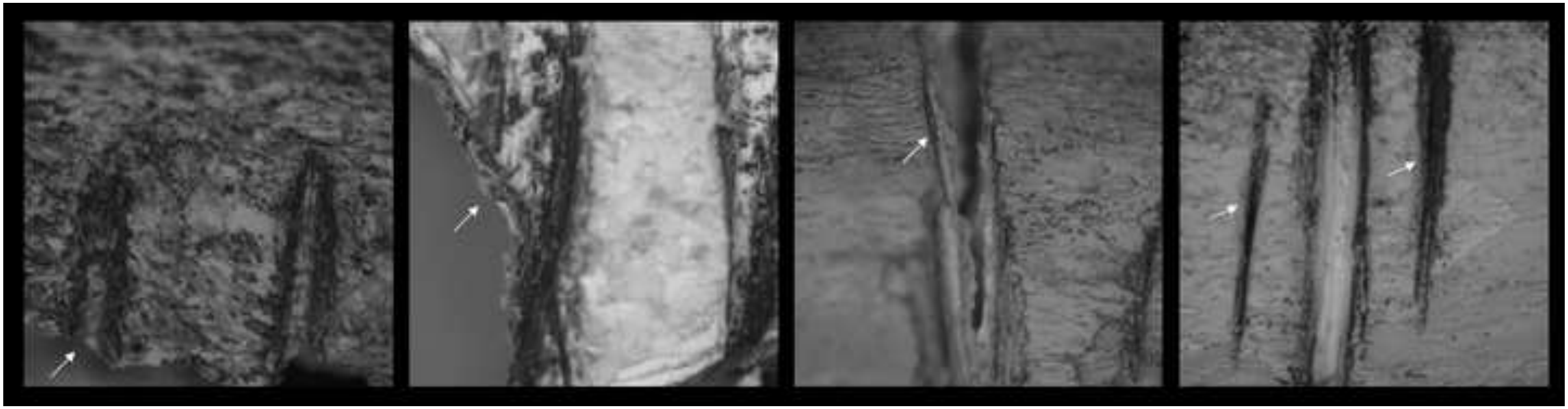
Click here to access/download;Figure;Fig 6 - Serrated knife.PNG

Fig 7

Click here to access/download;Figure;Fig 7 - Machete.PNG

Fig 8

Click here to access/download;Figure;Fig 8 - HIF.jpg



Figures

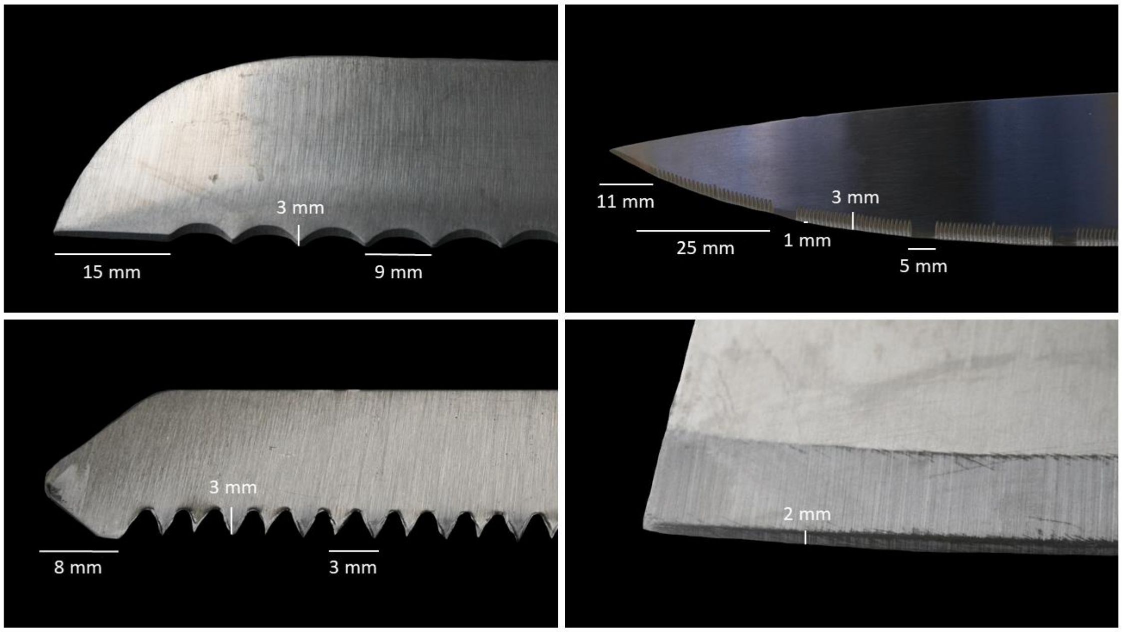


Fig. 1. **Tools used in this experiment**. Top left: Bread knife (BK) with coarse serration and a 210 mm blade length. Bottom left: Saw (S) with coarse serration and a 180 mm blade length. Top right: Serrated knife (SK) with fine serration and a 198 mm blade length. Bottom right: Machete (M) with no serration and a 136 mm blade length.

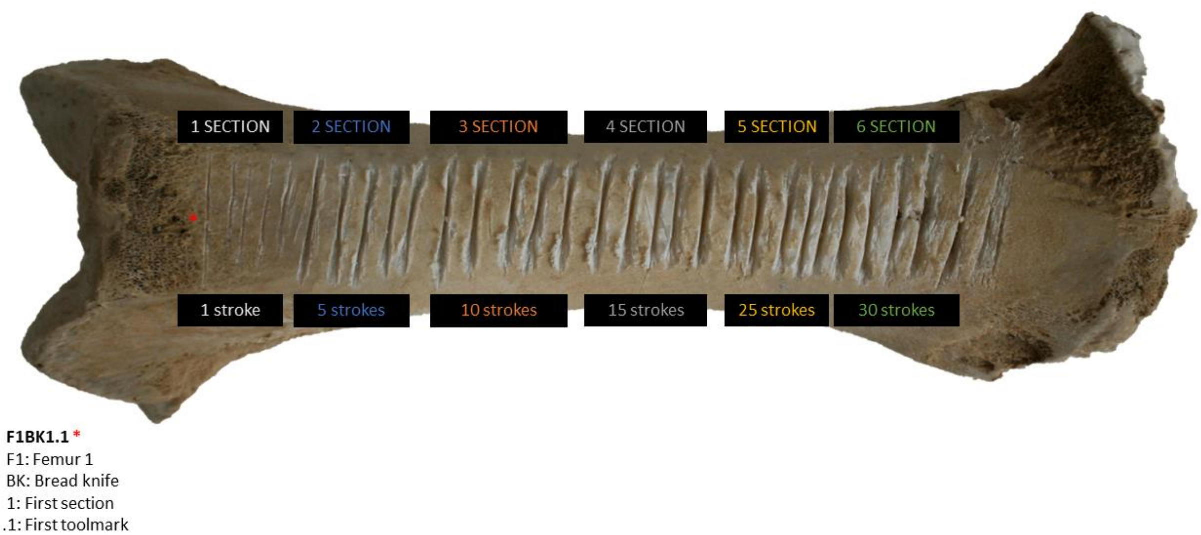


Fig. 2. **Experiment design**. A total of 30 cut marks were inflicted on each bone according to the controlled cutting action described in Norman et al. [19] A stroke is considered one "to-and-fro" motion. Each bone was divided in six sections with five repetitions.

Fig. 3. **Burning process.** The samples were placed in the following order from back to front: Tibia_2 (T2M); Tibia_1 (T1SK); Femur_2 (F2S) and Femur_1 (F1BK). The first image depicts the beginning of the burning process at 39 ºC. Combustion of the organic matter occurred ~30 min later and calcination after ~1 h. Heat-induced fractures were observed after carbonisation, starting from the lesions closest to the epiphyses. After 78 min, the samples achieved their definitive whitish colouration. The burning process finished after 247 min and the bones were left to cooldown overnight.

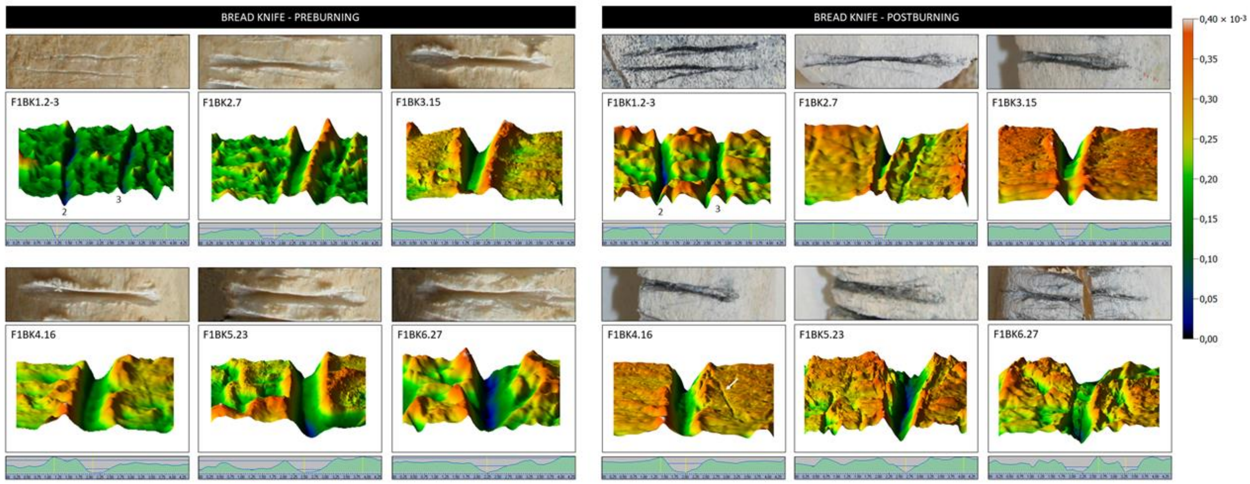


Fig. 4. Femur cut with a bread knife (F1BK). This figure depicts the morphology and roughness of one randomly selected cut mark of each femur section (1–6) before and after the burning process. The colour bar represents the depth of each cut mark. It can be observed that superficial cuts induced with the bread knife had a noticeable V-shape, whereas the floor shape of deep cuts varied greatly. After burning, the toolmarks exhibited irregular shapes and greater roughness. The unintentional false-start of F1BK4.16 was enhanced after the burning process (white arrow) and F1BK6.27 was ruptured by a longitudinal fracture.

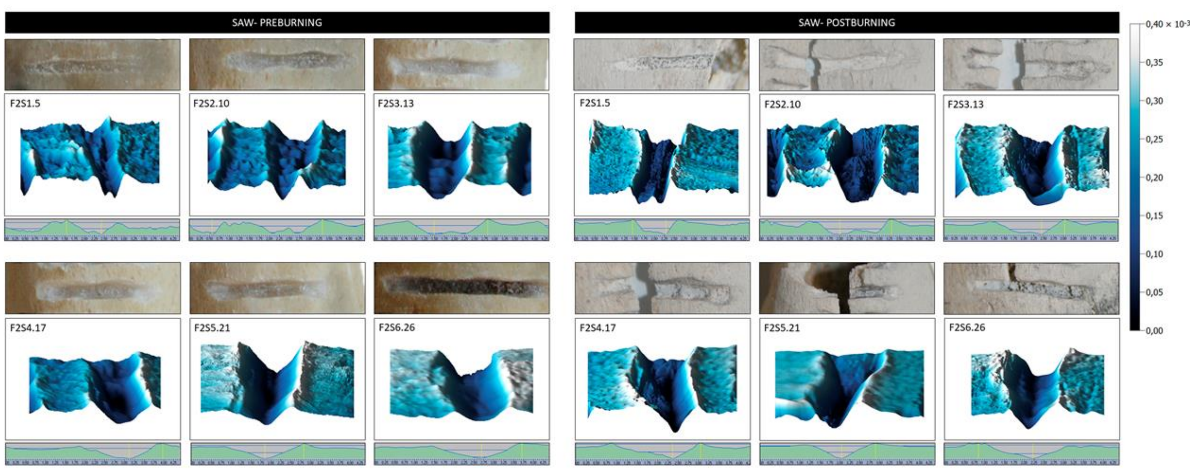


Fig. 5. **Femur cut with a saw** (F2S). This figure depicts the morphology and roughness of one randomly selected saw mark of each femur section (1–6) before and after the burning process. The colour bar represents the depth of each saw mark. It was noticed that superficial injuries had a W-shape, whereas deep cuts exhibited a U- or wide V-shape. After burning, the saw marks showed greater roughness overall but preserved the floor shape. All selected toolmarks were broken in half by longitudinal heat-induced fractures, except for F2S6

Fig. 6. **Tibia cut with a serrated knife** (T1SK). This figure depicts the morphology and roughness of one randomly selected cut mark of each tibia section (1–6) before and after the burning process. The colour bar represents the depth of each cut mark. Overall, all cuts induced with the serrated knife exhibited a V-shape and were narrower on superficial marks. After burning, the toolmarks showed greater roughness and sharper walls. T1SK2.8-9 were damaged by a longitudinal fracture.

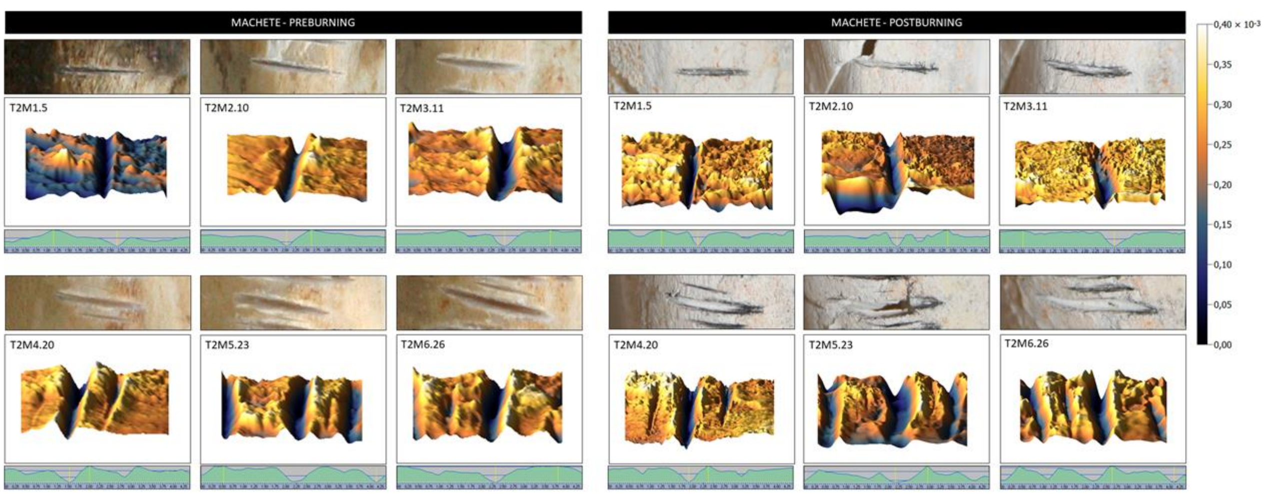


Fig. 7. **Tibia cut with a machete** (T2M). This figure depicts the morphology and roughness of one randomly selected cut mark of each tibia section (1–6) before and after the burning process. The colour bar represents the depth of each cut mark. Cuts induced with the machete exhibited a V-shape, with the floor becoming progressively rounded as the trauma deepened. After burning, the toolmarks showed greater roughness and even rounder floor shapes. T1SK2.10 and T2M5.23 were broken by heat-induced fractures.

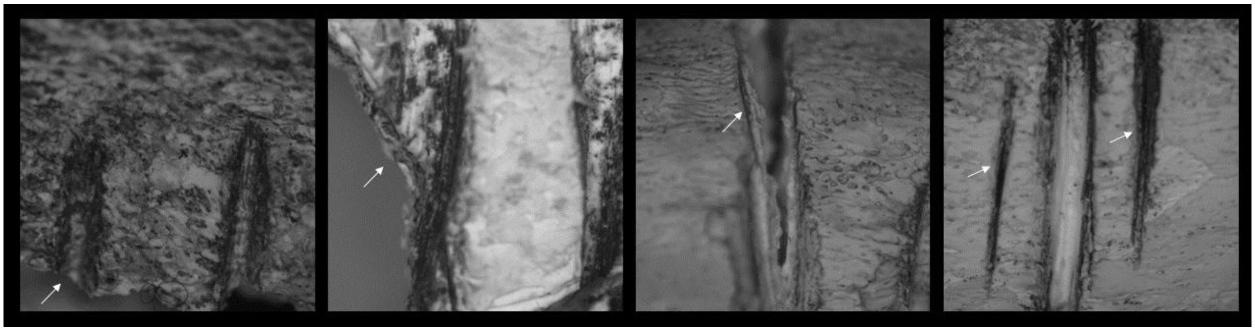


Fig 8. **Heat-induced changes observed after the burning process**. The first image shows a longitudinal fracture that transects two pre-existing cuts (T1SK2.7-8). The second depicts a transverse fracture that breaks in half the pre-existing cut (F1BK2.8). The third shows a widened cut mark (T1SK3.11). The fourth points to two unintentional false-start marks that had been enhanced and are more visible after burning (T2M4.20).

Tables:

Table 1: **Descriptive statistics**. Measurements before and after the burning process for each bone section.

Tool	S	Pre-burning			Post-burning			
		Length (mm)	Width (µm)	Roughness-Rz (µm)	Length (mm)	Width (µm)	Roughness-Rz (µm)	HIF
Bread knife	1	15.55 ± 2.41	33.20 ± 6.21	25.12 ± 4.48	13.13 ± 1.99	44.20 ± 9.22	23.16 ± 9.30	4/5
	2	17.12 ± 1.24	78.50 ± 15.15	23.48 ± 1.56	13.93 ± 1.85	63.60 ± 10.27	28.84 ± 7.30	3/5
	3	16.31 ± 0.68	99.40 ± 24.15	24.68 ± 0.75	11.23 ± 1.57	81.50 ± 10.74	35.40 ± 6.67	5/5
	4	15.40 ± 0.54	113.80 ± 25.04	22.65 ± 1.22	9.85 ± 1.02	91.70 ± 6.66	37.28 ± 1.72	5/5
	5	15.53 ± 0.53	118.80 ± 11.39	24.74 ± 1.47	10.00 ± 0.51	93.90 ± 11.07	38.25 ± 2.39	5/5
	6	18.45 ± 1.91	136.00 ± 12.60	20.51 ± 1.33	16.11 ± 1.09	93.38 ± 9.19	40.53 ± 6.09	5/5
Saw	1	12.04 ± 2.05	127.25 ± 15.52	16.24 ± 4.78	9.56 ± 1.26	128.80 ± 14.82	27.75 ± 4.63	2/5
	2	13.99 ± 0.17	185.60 ± 16.04	17.48 ± 3.30	11.14 ± 1.01	152.25 ± 10.16	25.74 ± 3.53	5/5
	3	13.55 ± 0.22	185.40 ± 13.26	17.95 ± 1.69	10.21 ± 0.45	169.60 ± 11.67	27.97 ± 3.00	5/5
	4	13.23 ± 0.66	204.60 ± 5.31	18.08 ± 0.97	9.74 ± 0.71	183.20 ± 12.62	29.98 ± 3.49	5/5
	5	12.95 ± 0.57	203.40 ± 16.16	23.49 ± 3.26	9.27 ± 1.27	180.40 ± 14.51	31.06 ± 3.57	5/5
	6	17.74 ± 0.61	214.50 ± 2.86	39.77 ± 9.17	15.16 ± 0.75	212.67 ± 11.15	26.87 ± 4.10	3/5
Serrated knife	1	7.76 ± 1.79	19.50 ± 2.85	9.45 ± 2.60	5.92 ± 0.97	41.80 ± 4.79	26.21 ± 3.44	2/5
	2	7.80 ± 0.55	61.30 ± 16.58	19.07 ± 3.60	6.04 ± 0.98	65.90 ± 9.43	37.90 ± 3.41	5/5
	3	8.00 ± 0.68	91.40 ± 5.05	20.85 ± 2.46	6.27 ± 0.85	77.30 ± 19.39	39.86 ± 4.97	1/5
	4	8.82 ± 0.55	85.70 ± 7.70	20.85 ± 6.05	7.33 ± 0.31	72.90 ± 10.11	37.24 ± 3.70	0/5
	5	8.95 ± 0.78	116.50 ± 19.93	15.02 ± 2.17	7.71 ± 0.74	89.10 ± 15.75	39.85 ± 3.22	0/5
	6	9.78 ± 0.33	103.10 ± 5.08	13.48 ± 1.23	8.51 ± 0.45	104.20 ± 12.94	44.79 ± 2.68	0/5
Machete	1	6.15 ± 0.50	25.90 ± 3.44	22.39 ± 0.61	5.21 ± 0.43	56.80 ± 4.63	33.19 ± 1.27	0/5
	2	7.77 ± 1.51	58.20 ± 14.33	17.82 ± 2.83	6.21 ± 1.52	60.25 ± 4.10	34.45 ± 4.96	5/5
	3	7.79 ± 0.58	70.00 ± 9.88	16.60 ± 1.30	6.50 ± 0.29	85.90 ± 23.35	49.03 ± 5.26	0/5
	4	7.97 ± 0.38	86.10 ± 19.34	17.58 ± 1.06	5.97 ± 0.32	92.20 ± 15.35	50.50 ± 5.75	0/5
	5	7.38 ± 1.41	79.80 ± 16.80	19.16 ± 2.16	6.88 ± 0.87	79.60 ± 21.88	44.54 ± 2.78	3/5
	6	9.55 ± 0.43	83.10 ± 16.54	19.47 ± 1.60	8.16 ± 0.23	101.80 ± 25.65	35.62 ± 2.41	0/5

S: Bone section; HIF: Number of heat-induced fractures affecting toolmarks in each section.

Table 2: **Descriptive statistics**. Student's t-test (sig.)

Tool	Variables	Burning process	N	Mean	Min	Max	SD	Sig.
Bread knife	Length (mm)	Pre-burning	30	16.393	12.880	20.440	1.820	0.000[a]
		Post-burning	30	12.376	8.630	17.360	2.711	
	Width (µm)	Pre-burning	30	96.617	25.000	159.000	38.198	0.022[a]
		Post-burning	29	77.517	32.000	110.000	21.258	
	Roughness-Rz (Rz)	Pre-burning	30	23.529	18.130	31.580	2.745	0.000[a]
		Post-burning	30	33.912	12.898	48.258	8.343	
Saw	Length (mm)	Pre-burning	28	13.642	8.640	18.530	1.860	0.000[a]
		Post-burning	28	10.538	6.950	16.120	2.009	
	Width (µm)	Pre-burning	28	184.813	102.000	233.000	32.055	0.055
		Post-burning	27	168.778	104.000	222.000	28.418	
	Roughness-Rz (µm)	Pre-burning	28	20.910	11.385	52.735	8.268	0.000[a]
		Post-burning	28	28.326	19.402	36.015	4.226	
Serrated knife	Length (mm)	Pre-burning	30	8.517	5.870	10.730	1.192	0.000[a]
		Post-burning	30	6.964	4.370	9.220	1.243	
	Width (µm)	Pre-burning	30	79.583	15.000	144.000	34.311	0.567
		Post-burning	30	75.200	37.000	121.000	23.677	
	Roughness-Rz (µm)	Pre-burning	30	16.452	6.700	27.110	5.480	0.000[a]
		Post-burning	30	37.640	20.035	49.415	6.836	
Machete	Length (mm)	Pre-burning	30	7.769	4.960	9.980	1.388	0.000[a]
		Post-burning	30	6.490	4.520	8.490	1.204	
	Width (µm)	Pre-burning	30	67.183	23.000	124.500	25.622	0.055
		Post-burning	29	80.086	51.500	132.000	24.865	
	Roughness-Rz (µm)	Pre-burning	30	18.835	14.290	22.920	2.599	0.000[a]
		Post-burning	26	40.594	26.085	58.160	8.239	

[a] $p \leq 0.05$, Student t-test shows high significance between pre-burning and post-burning Length and Roughness means.

Table 3: **Univariate analysis of variance**. Post hoc test.

(A) Tests of between-subjects effects

Dependent variable	Mean square	*F*	Sig.
Pre-burning Length	510.335	203.045	0.000[ab]
Post-burning Length	240.304	66.971	0.000[ab]
Pre-burning Width	80896.522	74.833	0.000[ab]
Post-burning Width	57404.163	94.794	0.000[ab]
Pre-burning Roughness	271.437	9.884	0.000[ab]
Post-burning Roughness	768.325	15.220	0.000[ab]

(B) Multiple comparisons

		Pre-burning Length					**Post-burning Length**				
					95% confidence interval					**95% confidence interval**	
Tool (I)	**Tools (J)**	**Mean diff. (I-J)**	**Std. error**	**Sig.**	**Upper bound**	**Lower Bound**	**Mean diff. (I-J)**	**Std. error**	**Sig.**	**Upper bound**	**Lower Bound**
BK	S	2,7512	0.41659	0.000	1.63265	3.86978	1,8382	0.49775	0.002	0.50167	3.17466
	SK	7,8760	0.40934	0.000	6.77689	8.97511	5,4120	0.48909	0.000	4.09875	6.72525
	M	8,6240	0.40934	0.000	7.52489	9.72311	5,8857	0.48909	0.000	4.57241	7.19892
S	BK	-2,7512	0.41659	0.000	-3.86978	-1.63265	-1,8382	0.49775	0.002	-3.17466	-0.50167
	SK	5,1248	0.41659	0.000	4.00622	6.24335	3,5738	0.49775	0.000	2.23734	4.91033
	M	5,8728	0.41659	0.000	4.75422	6.99135	4,0475	0.49775	0.000	2.71100	5.38400
SK	BK	-7,8760	0.40934	0.000	-8.97511	-6.77689	-5,4120	0.48909	0.000	-6.72525	-4.09875
	S	-5,1248	0.41659	0.000	-6.24335	-4.00622	-3,5738	0.49775	0.000	-4.91033	-2.23734
	M	0.7480	0.40934	0.422[c]	-0.35111	1.84711	0.4736	0.48909	1.000[d]	-0.83959	1.78692
M	BK	-8,6240	0.40934	0.000	-9.72311	-7.52489	-5,8857	0.48909	0.000	-7.19892	-4.57241
	S	-5,8728	0.41659	0.000	-6.99135	-4.75422	-4,0475	0.49775	0.000	-5.38400	-2.71100
	SK	-0.7480	0.40934	0.422[c]	-1.84711	0.35111	-0.4736	0.48909	1.000[d]	-1.78692	0.83959

**Post hoc tests.

[a] ANOVA produced a p value of ≤ 0.05, indicating a significant difference between tools and length.

[b] $p \leq 0.05$, indicates that it is necessary to determine whether the tool type influences length by post hoc tests.

[c] $p > 0.05$, shows no significant differences between serrated knife and machete respect to pre-burning length.

[d] $p > 0.05$, shows no significant differences between serrated knife and machete respect to post-burning length.

		Pre-burning Width					**Post-burning Width**				
					95% confidence interval					**95% confidence interval**	
Tool (I)	**Tools (J)**	**Mean diff. (I-J)**	**Std. error**	**Sig.**	**Upper bound**	**Lower Bound**	**Mean diff. (I-J)**	**Std. error**	**Sig.**	**Upper bound**	**Lower Bound**
BK	S	-88,1958	8.63956	0.000	-111.39371	-64.99795	-91,2605	6.58105	0.000	-108.93963	-73.58144
	SK	17.0333	8.48929	0.283[c]	-5.76107	39.82774	2.31724	6.40838	1.000[d]	-14.89801	19.53249
	M	29,4333	8.48929	0.004	6.63893	52.22774	-2.56897	6.46246	1.000[d]	-19.92949	14.79156
S	BK	88,1958	8.63956	0.000	64.99795	111.39371	91,2605	6.58105	0.000	73.58144	108.93963
	SK	105,2292	8.63956	0.000	82.03129	128.42705	93,5778	6.52795	0.000	76.04132	111.11423
	M	117,6292	8.63956	0.000	94.43129	140.82705	88,6916	6.58105	0.000	71.01247	106.37067
SK	BK	-17.0333	8.48929	0.283[c]	-39.82774	5.76107	-2.3172	6.40838	1.000[d]	-19.53249	14.89801
	S	-105,2292	8.63956	0.000	-128.42705	-82.03129	-93,5778	6.52795	0.000	-111.11423	-76.04132
	M	12.4000	8.48929	0.881[c]	-10.39441	35.19441	-4.8862	6.40838	1.000[d]	-22.10146	12.32904
M	BK	-29,4333	8.48929	0.004	-52.22774	-6.63893	2.56897	6.46246	1.000[d]	-14.79156	19.92949
	S	-117,6292	8.63956	0.000	-140.82705	-94.43129	-88,6916	6.58105	0.000	-106.37067	-71.01247
	SK	-12.4000	8.48929	0.881[c]	-35.19441	10.39441	4.8862	6.40838	1.000[d]	-12.32904	22.10146

**Post hoc tests.

[a] ANOVA produced a p value of ≤ 0.05, indicating a significant difference between tools and width.

[b] $p \leq 0.05$, indicates that it is necessary to determine whether the tool type influences width by post hoc tests.

[c] $p > 0.05$, shows no significant differences between bread knife and serrated knife, and between serrated knife and machete respect to pre-burning width.

[d] $p > 0.05$, shows no significant differences between bread knife, machete, and serrated knife, and between serrated knife and machete respect to post-burning width.

		Pre-burning Roughness					Post-burning Roughness				
					95% confidence interval					95% confidence interval	
Tool (I)	**Tools (J)**	**Mean diff. (I-J)**	**Std. error**	**Sig.**	**Upper bound**	**Lower Bound**	**Mean diff. (I-J)**	**Std. error**	**Sig.**	**Upper bound**	**Lower Bound**
BK	S	2.6185	1.37703	0.358[c]	-1.07886	6.31602	5,5859*	1.86698	0.021	0.56968	10.6021
	SK	7,0770	1.35308	0.000	3.44384	10.71010	-3.72822	1.83450	0.267[d]	-8.65718	1.20074
	M	4,6937	1.35308	0.004	1.06056	8.32683	-6,6814*	1.90375	0.004	-11.79640	-1.56635
S	BK	-2.6185	1.37703	0.358[c]	-6.31602	1.07886	-5,5859*	1.86698	0.021	-10.60209	-0.56968
	SK	4,4584	1.37703	0.009	0.76095	8.15583	-9,3141*	1.86698	0.000	-14.33031	-4.29790
	M	2.0751	1.37703	0.808[c]	-1.62233	5.77255	-12,2673*	1.93506	0.000	-17.46640	-7.06811
SK	BK	-7,0770	1.35308	0.000	-10.71010	-3.44384	3.72822	1.83450	0.267[d]	-1.20074	8.65718
	S	-4,4584	1.37703	0.009	-8.15583	-0.76095	9,3141*	1.86698	0.000	4.29790	14.33031
	M	-2.3832	1.35308	0.485[c]	-6.01641	1.24985	-2.95315	1.90375	0.742[d]	-8.06817	2.16187
M	BK	-4,6937	1.35308	0.004	-8.32683	-1.06056	6,6814*	1.90375	0.004	1.56635	11.79640
	S	-2.0751	1.37703	0.808[c]	-5.77255	1.62233	12,2673*	1.93506	0.000	7.06811	17.46640
	SK	2.3832	1.35308	0.485[c]	-1.24985	6.01641	2.95315	1.90375	0.742[d]	-2.16187	8.06817

**Post hoc tests.

[a] ANOVA produced a p value of ≤ 0.05, indicating a significant difference between tools and roughness.

[b] $p \leq 0.05$, indicates that it is necessary to determine whether the tool type influences roughness by post hoc tests.

[c] $p > 0.05$, shows no significant differences between bread knife and saw, between saw and machete, and between serrated knife and machete respect to pre-burning roughness.

[d] $p > 0.05$, shows no significant differences between bread knife and serrated knife, and between serrated knife and machete respect to post-burning roughness.

Annex with captions

Click here to access/download
Supplementary Material
Cutmarks_Supplementary material.docx

Annex 2

Click here to access/download
Supplementary Material
Annex 2 - Bones before and after the burning process.png

Annex 3

Annex 5

Click here to access/download
Supplementary Material
Annex 5 - Roughness.PNG