



# Using horse teeth to shape stone tools: an experimental approach to characterise use-wear traces

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## Abstract

Horse tooth retouchers have been identified in several Middle and Upper Palaeolithic sites. They have been typically characterised as ‘soft’ hammers and/or grouped into the category of ‘bone retouchers’ at a technical level. Bone and teeth have different chemical compositions; teeth are denser and heavier than bone, and consequently, their technological features should not be considered homologous. In this work, we experimentally tested the effectiveness of horse teeth as retouchers. To perform this study, we used 41 modern horse teeth to shape flakes of various raw materials by applying different techniques. The resulting use-wear traces were analysed using high-resolution methods and then characterised. The results allowed us to identify the effectiveness of hypsodont teeth in knapping a wide range of tools and to evaluate the influence of 1) the raw materials, 2) the retouching techniques and 3) the gestures of the different knappers on the morphology of the use-wear marks. This work sheds light on the purpose of using teeth as tools by both Neanderthal and early modern human populations as well as understanding how these human species used them. The study leads us to consider tooth retouchers as important elements of the *chaîne opératoire* in lithic manufacture. Our goal is to highlight the importance of these types of experimental studies to create analogies and infer past processes.

**Keywords** Experimental archaeology · Horse tooth retouchers · Use-wear traces · Middle Palaeolithic · Upper Palaeolithic · Knapping

## Introduction

Retouchers used in the creation and maintenance of lithic tools were prevalent in the late Lower Palaeolithic in Europe and the Levant as early as MIS 13 (*e.g.* Roberts and Parfitt 1999; Smith 2013; Stout et al. 2014; Rosell et al. 2018).

These tools became widespread during the Middle Palaeolithic in Eurasia (Mallye et al. 2012; Mozota 2012; Abrams et al. 2014; Daujeard et al. 2014, 2018; Costamagno et al. 2018; Doyon et al. 2018; Neruda and Lázníčková-Galetová 2018; Turner et al. 2020). Thus, they have mainly been associated with Neanderthal cave sites, such as La Quina, where these items were first recognised by French archaeologists in the early years of the twentieth century (Henri-Martin 1906, 1907). During the Upper Palaeolithic, as well as in other Holocene contexts, they continued being used (*e.g.* Castel et al. 2003; Castel and Madelaine 2006; Tartar 2012; Jéquier et al. 2012; Zhang et al. 2018; Bello et al. 2021). These tools vary in material, function and typology (retouchers, compressors, hammers). Patou-Mathis and Schwab (2002, pp. 11) defined retouchers as ‘fragments of teeth, long bones, phalanges or ribs of big mammals, which present on their exteriors one or more impressed areas, related to crushing marks, and/or cupules, and/or scores, without modification of initial morphology, made by impact against a sharp and hard artefact with the edge of flake, tool or handaxe’. Turner

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et al. (2020) defined them as ‘artefacts made of vertebrate hard tissues such as bone, as well as teeth, antler and ivory’. They were used as intermediaries to shape and/or refine stone tools through percussion or pressure and could be used in place of stone hammers in the lithic *chaîne opératoire* (Hutson et al. 2018).

Several experiments have been typically and widely performed to understand why and how these bone tools were used, focusing on successfully correlating the morphology of the taphonomic alterations with a number of variables, such as the grip (Kolobova et al. 2022), the condition of the bone (fresh or dry; Villa and Mahieu 1991; Mallye et al. 2012; Mozota 2013), the type of activity (Mateo-Lomba et al. 2020), the type of retouched lithic raw material (Rosell et al. 2011; Mallye et al. 2012; Mozota 2013), the retouch type (e.g. simple, pressure, Quina-type retouch; Boëda and Vicent 1990; Bourguignon 2001; Ahern et al. 2004; Tartar 2012; Mozota 2013), the retouching methods and techniques (e.g. Siret 1925; Semenov 1956; Leonardi 1979; Ahern et al. 2004; Veselsky 2008; David and Pelegrin 2009), right–left laterality (Semenov 1956; Rigaud 1977; Malerba and Giacobini 2002; Mozota 2009; Mozota 2012; Mozota 2013), the preparation and collection of blanks (Vincent 1993; Armand and Delagnes 1998; Mozota 2013), the taxonomy and anatomical parts of the bone tools used (Valensi 2002; Rosell et al. 2011; Mozota 2013) and the dimensions of the bone retoucher (e.g. Veselsky 2008; Mozota 2013). These approaches, combined with analyses of archaeological retouchers, have provided vital information on the subsistence strategies, economic behaviours and cognitive capabilities of past human groups (e.g. Mozota 2009; Jéquier et al. 2012; Mallye et al. 2012; Mozota 2015).

Despite the significant contributions made in this area during recent decades, experimental studies have overlooked tooth and ivory as raw materials, which is not unexpected, since in the archaeological record, the identification of use traces on dental surfaces is uncommon. Tooth material used as hammers from archaeological deposits are represented by the hypsodont teeth of horses, the teeth of wild boar, the canines of large carnivores, and mammoth tusks. An interesting example can be found at the archaeological site of Laugerie-Haute (Les-Eyzies-de-Tayac, Dordogne, France), where two horse (*Equus caballus*) tooth retouchers from the Solutrean units were recovered (a first and a second right lower molar; Castel and Madelaine 2006). According to Castel and Madelaine (2006), the scars on these teeth were similar to those found on bone retouchers from Mousterian and Aurignacian layers. The authors suggested paying close attention to this type of material, since it may go undetected (Castel and Madelaine 2006). In La Ferrassie (Savignac-de-Miremont, Dordogne, France) two horse (*E. caballus*) tooth retouchers were identified in Aurignacian layers; these were an upper-right molar (first or second) and a lower-left

premolar (third or fourth; Castel et al. 2003). In Gough’s Cave (Somerset, UK), there were two horse (*Equus ferus*) tooth retouchers from Magdalenian layers, namely an upper third molar and an incisor (Bello et al. 2021). Verna and d’Errico (2011) cited another horse lower premolar from the Mousterian layers of La Quina (Charente, France). As for carnivore tooth retouchers, examples are scarce. They have been attributed to the Mousterian and Aurignacian contexts and belong mainly to the canines of *P. spelaea* and, to a lesser extent, *Ursus arctos* and *U. spelaeus* (Castel et al. 2003; Camarós et al. 2016; Toniato et al. 2018).

Tooth retouchers are typically included in the category of ‘bone retoucher’ (e.g. Patou-Mathis and Schwab 2002; Daujeard et al. 2014; Turner et al. 2020), and thus considered as ‘soft’ hammers. However, the difference in the chemical composition of bones and teeth should be considered when making these assessments. While it is true that not all bones have the same size and consistency, they are a calcified tissue composed of approximately 60% inorganic material (hydroxyapatite), 10% water and 30% organic material (proteins; e.g. Tolar et al. 2004; Zhu and Prince 2015). Dentine and enamel are composed of 70–80% hydroxyapatite crystals (e.g. Habibah et al. 2022); thus, teeth are denser and heavier than bone. Consequently, their technological features are not homologous, and their use as retouchers should be assessed.

It has been suggested that bone tools were specially selected and deliberately configured (Jéquier et al. 2012; Mozota 2015). Daujeard et al. (2014) highlighted this intentional approach by humans, as evidenced by their collection and use. Similar conclusions were proposed by Costamagno et al. (2018) for the assemblage of bone retouchers from Les Pradelles, suggesting that blanks had intentionally been selected for butchery purposes. Valensi (2002) presented a study of several phalanges of *Rangifer tarandus* and *Bos* sp. that had been used as retouchers. Each species was associated with a particular type of retouch; that is, the *Bos* phalanges were used to perform abrupt retouching, while *R. tarandus* were used for flat and invasive retouching. In light of all these considerations, it can be assumed that horse and carnivore teeth were also collected with a specific technological purpose. In addition, we should consider that, despite the scarce evidence in the archaeological records, these cases were not isolated during the Middle and Upper Palaeolithic, and they show apparently convenient features for knapping (elongated, curved, heavy and dense) due to the high crown of these teeth (hypsodont teeth).

The aim of this work is to experimentally test the effectiveness of horse teeth as retouchers and their impact on the manufacture of lithic tools. Understanding how teeth were used as tools will complement the more traditional approaches for interpreting stone tool technologies, and it will also provide a new perspective for discussions about the

technical abilities of Neanderthals and early modern human populations. In addition, use traces have been characterised and compared with those produced on bone in order to better understand the formation and development of use-wear traces on materials with different physical features. The results of this paper lead us to consider tooth retouchers as being important elements within the *chaîne opératoire* in lithic manufacture.

## Materials and methods

### Experimental protocol

Experimental studies have commonly been used to explore taphonomic processes affecting the archaeological record. These proxies help create analogies and infer past processes (Yellen 1977; Shipman 1981; Shipman and Rose 1983; Bonnichsen 1989; Andrews 1995; Domínguez-Rodrigo et al. 2009; Outram 2008; Blasco et al. 2008).

This experiment was performed at the Experimental Archaeology and Taphonomy Laboratory at the National Research Centre for Human Evolution (CENIEH) in Burgos, Spain. Five experienced experimental stone knappers retouched tools with 41 horse teeth consisting of upper premolars/molars ( $n=23$ ), lower premolars/molars ( $n=15$ ) and incisors ( $n=3$ ; Table 1). Each knapper had previous technical know-how on retouching flakes with stone retouchers, and only KN1 had know-how for using bone. In the experiment, all the knappers, who were all right-handed, retouched flakes with horse teeth for the first time.

Several comparative studies have focused on distinguishing the traces produced when retouching quartzite blanks from those produced from flint (Rosell et al. 2011; Mozota 2013; Mallye et al. 2012). In this experiment, we included two varieties of flint, as well as quartzite and quartz (although the latter has not been considered in previous studies), with their sources as follows:

- **Flint from Norfolk, East Anglia, UK (FN).** This is from chalk bedrock of the Turonian age (Healy et al. 2018) and shows a thick, creamy cortex and a fine grain. It is predominantly black and clear and occasionally grey, and fossil and chalky inclusions are relatively common. The fracture of this flint is consistent and highly predictable; thus, it is considered a high-quality material for knapping (Saville 1981, pp. 1–2; Snyder et al. 2023).
- **Flint from Ebro Valley, Zaragoza, Spain (FEV).** Several varieties of flint can be found in the Ebro Valley. The flint used in the experiment had pinkish or yellowish hues and is of poor quality to knap, since it comprises about 60% carbonates and 30% silica (Cuchí and Mazo 1992). These varieties of flint come from Miocene forma-

**Table 1** Sample used in the experiment, indicating item's label (UHR: Upper Horse Tooth Retoucher; LHTR: Lower Horse Tooth Retoucher; I: Incisor), knapper (KN1: Felipe Cuartero; KN2: Javier Llamazares; KN3: Luis Zalbidea; KN4: Pablo Sañudo; KN5: Cristian Micó), type of tooth (LM/P: Lower Molar/Premolar; UM/P: Upper Molar/Premolar; I: Incisor), knapped raw material used for each tooth (FN: Flint from Norfolk; FEV: Flint from Ebro Valley), the total number of products obtained (n), and the type of product (Scr: Scraper; PScr: Pointed Scraper; DQscr: Demi-Quina Scraper; Qscr: Quina Scraper; Den: Denticulate; Blad: bladelet; SP: Solutrean point; BP: Backed Point; BB: Backed Blade)

| ID_Item | Knapper | Tooth | Knapped raw material | Total of products (n) | Type of product |
|---------|---------|-------|----------------------|-----------------------|-----------------|
| LHTR1   | KN1     | LM/P  | Quartz               | 2                     | QScr            |
| LHTR2   | KN1     | LM/P  | Quartz               | 3                     | DQScr           |
| LHTR3   | KN1     | LM/P  | FN                   | 1                     | QScr            |
| LHTR4   | KN1     | LM/P  | FN                   | 2                     | QScr            |
| LHTR5   | KN1     | LM/P  | FN                   | 1                     | QScr            |
| LHTR6   | KN1     | LM/P  | FN                   | 29                    | Blad            |
| LHTR7   | KN1     | LM/P  | FN                   | 1                     | SP              |
| UHTR1   | KN1     | UM/P  | FN                   | 10                    | BP              |
| UHTR2   | KN1     | UM/P  | FN                   | 3                     | Scr, DQScr      |
| UHTR3   | KN1     | UM/P  | Quartzite            | 4                     | DQScr, QScr     |
| UHTR4   | KN1     | UM/P  | Quartzite            | 1                     | QScr            |
| UHTR5   | KN1     | UM/P  | FN                   | 4                     | BB              |
| UHTR6   | KN1     | UM/P  | Quartz               | 1                     | Qscr            |
| LHTR8   | KN2     | LM/P  | FN                   | 3                     | PScr, Scr       |
| LHTR9   | KN2     | LM/P  | Quartzite            | 3                     | Scr             |
| LHTR10  | KN2     | LM/P  | Quartzite            | 4                     | DQScr, Den      |
| LHTR11  | KN2     | LM/P  | Quartz               | 1                     | Scr             |
| LHTR12  | KN2     | LM/P  | FN                   | 3                     | DQScr, Scr      |
| LHTR13  | KN2     | LM/P  | FN                   | 3                     | Scr, DQScr      |
| UHTR7   | KN2     | UM/P  | FN                   | 22                    | Blad            |
| UHTR8   | KN2     | UM/P  | FN                   | 1                     | Scr             |
| UHTR9   | KN2     | UM/P  | Quartzite            | 10                    | Scr, Den, DQScr |
| UHTR10  | KN2     | UM/P  | FN                   | 2                     | Scr, Den        |
| UHTR11  | KN2     | UM/P  | Quartzite            | 1                     | DQScr           |
| UHTR12  | KN2     | UM/P  | FN                   | 4                     | Scr             |
| UHTR13  | KN2     | UM/P  | Quartzite            | 2                     | Scr, Den        |
| IHTR1   | KN3     | I     | FEV                  | 2                     | DQScr, Scr      |
| IHTR2   | KN3     | I     | FEV                  | 1                     | Scr             |
| UHTR14  | KN3     | UM/P  | FEV                  | 2                     | PScr, PScr      |
| UHTR15  | KN3     | UM/P  | Quartz               | 2                     | DQScr           |
| UHTR16  | KN3     | UM/P  | Quartz               | 1                     | Scr             |
| UHTR17  | KN3     | UM/P  | FEV                  | 1                     | DQScr           |
| IHTR3   | KN4     | I     | FEV                  | 1                     | Scr             |
| UHTR18  | KN4     | UM/P  | FEV                  | 1                     | DQScr           |
| UHTR19  | KN4     | UM/P  | FEV                  | 1                     | DQScr           |
| LHTR14  | KN5     | LM/P  | FN                   | 1                     | QScr            |
| LHTR15  | KN5     | LM/P  | FN                   | 2                     | QScr, Scr       |
| UHTR20  | KN5     | UM/P  | FEV                  | 1                     | PScr            |
| UHTR21  | KN5     | UM/P  | FEV                  | 1                     | DQScr           |
| UHTR22  | KN5     | UM/P  | FEV                  | 2                     | PScr, Scr       |
| UHTR23  | KN5     | UM/P  | Quartzite            | 3                     | DQScr, QScr     |

tions and surfaced in the middle Ebro Basin (Picazo et al. 2020).

- **Quartzite from Olmos de Atapuerca, Burgos, Spain.** This is from the Early Cretaceous Utrillas facies formation that is variety 1, according to Perdegnana et al. (2017). It consists almost completely of angular to sub-angular quartz grains (95%) that range from 50 to 100 mm (Perdegnana et al. 2017). The crystalline texture is granular, and it exhibits a granoblastic bimodal quartz mosaic (Yardley et al. 1990).
- **Quartz from Moiá, Barcelona, Spain.** This is from conglomerate levels of the Eocene age (Bartonian), which are outcrops at the northwest of the town of Castellterçol. It occurs as pebbles within the conglomerates together with other lithologies and varies between milky quartz, which may or may not have oxides, and blue quartz.

First, high-resolution moulds of the tooth surfaces were made to record the initial conditions and enable comparisons with the surfaces after the experiment. Before moulding, the occlusal surface of each tooth was cleaned using acetone and then 96% ethanol. The surface was then moulded with high-resolution silicone (vinyl polysiloxane; Provil Novo Light, regular set), and transparent casts were produced using clear epoxy resin (CTS EPO 150) (Fig. 1).

The experimenters were only given guidelines about the type of lithic tools to be knapped (typical tools from the Middle and Upper Palaeolithic), to influence the experiment as little as possible. Thus, each knapper freely used different gestures and teeth surfaces to manufacture the tools (Fig. 2). Flakes were obtained following discoid and Levallois methods. Also, knapping techniques included direct percussion and pressure flaking.

After each retouching activity, silicon moulds were created to record the formation, development and overlap of

use-wear traces as well as to identify the lifespan of the teeth. The detailed process of the experiment can be found in Table S1.

### Resulting lithic tools: tool types and mode of retouch

In total, 143 tools were knapped, including 51 bladelets, 27 scrapers, 24 demi-Quina scrapers, 16 Quina scrapers, 10 backed points, 5 denticulates, 5 pointed scrapers, 4 backed blades and 1 Solutrean point (Fig. 3).

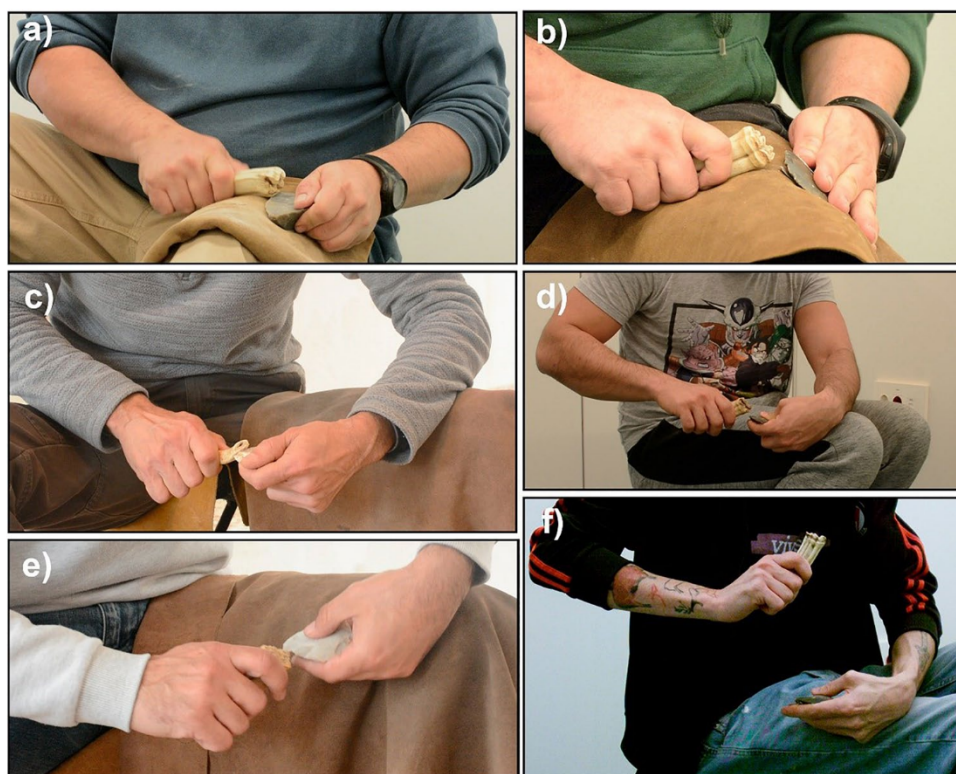
The high quality of the flint from Norfolk allowed a broad variety of retouch types, and 92 tools were obtained. The scrapers tended to show the same features (Fig. 4b) and presented a long and/or invasive retouch as well as a low angle in the removals. The orientation was mostly direct, and only on very few occasions was it inverse. Quina and demi-Quina scrapers showed the traditional features proposed by Bordes (1961), namely ‘a scalar retouch that is more or less developed’ (Fig. 4a). The high quality of this flint also allowed the extraction of bladelets as well as the manufacture of backed points, blades and a Solutrean point through removals that were invasive and covered a lot of surface. Although the extraction of bladelets was possible, the flaked surface resulted in hinge terminations during knapping. According to the knappers, the hinged terminations are a direct consequence of the use of horse teeth, the size of which makes it difficult to execute precise blows.

In contrast, in the quartzite, only scrapers and demi-Quina and Quina scrapers were made as a consequence of the characteristics of the raw material. Twenty-eight pieces were retouched. However, the teeth also allowed for long and invasive removals as well as a long angle retouch and demi-Quina and Quina retouch (Fig. 4c).



**Fig. 1** Process of moulding and analysis of the teeth surfaces after being used during the experiment: **a)** moulding with high-resolution silicone (vinyl polysiloxane; Provil Novo Light, regular set); **b)** dried

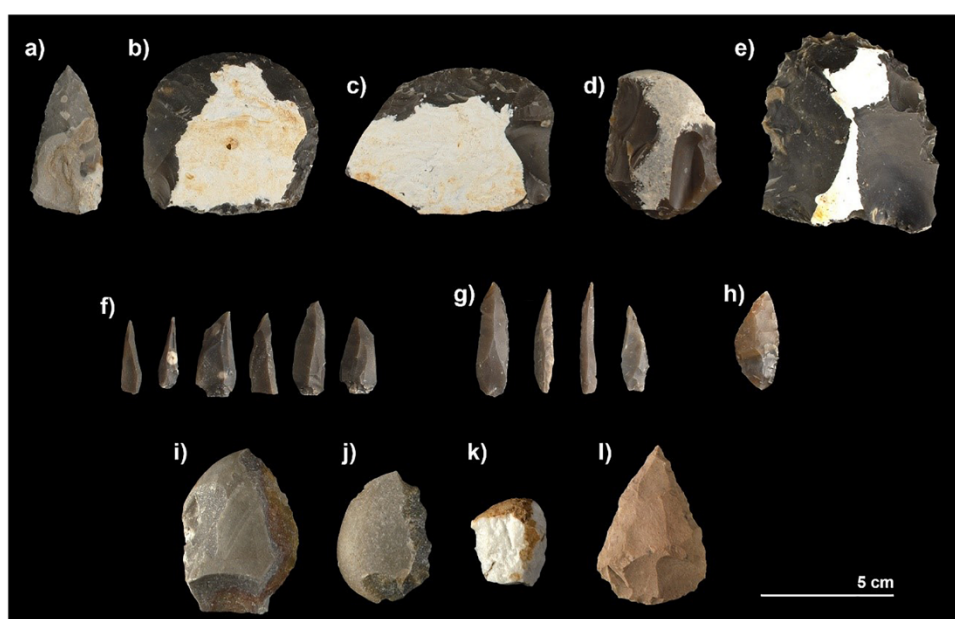
transparent casts produced using clear epoxy resin (CTS EPO 150); and **c)** examination of the transparent casts under transmitted light with a stereomicroscope (Zeiss Stemi 2000-C)

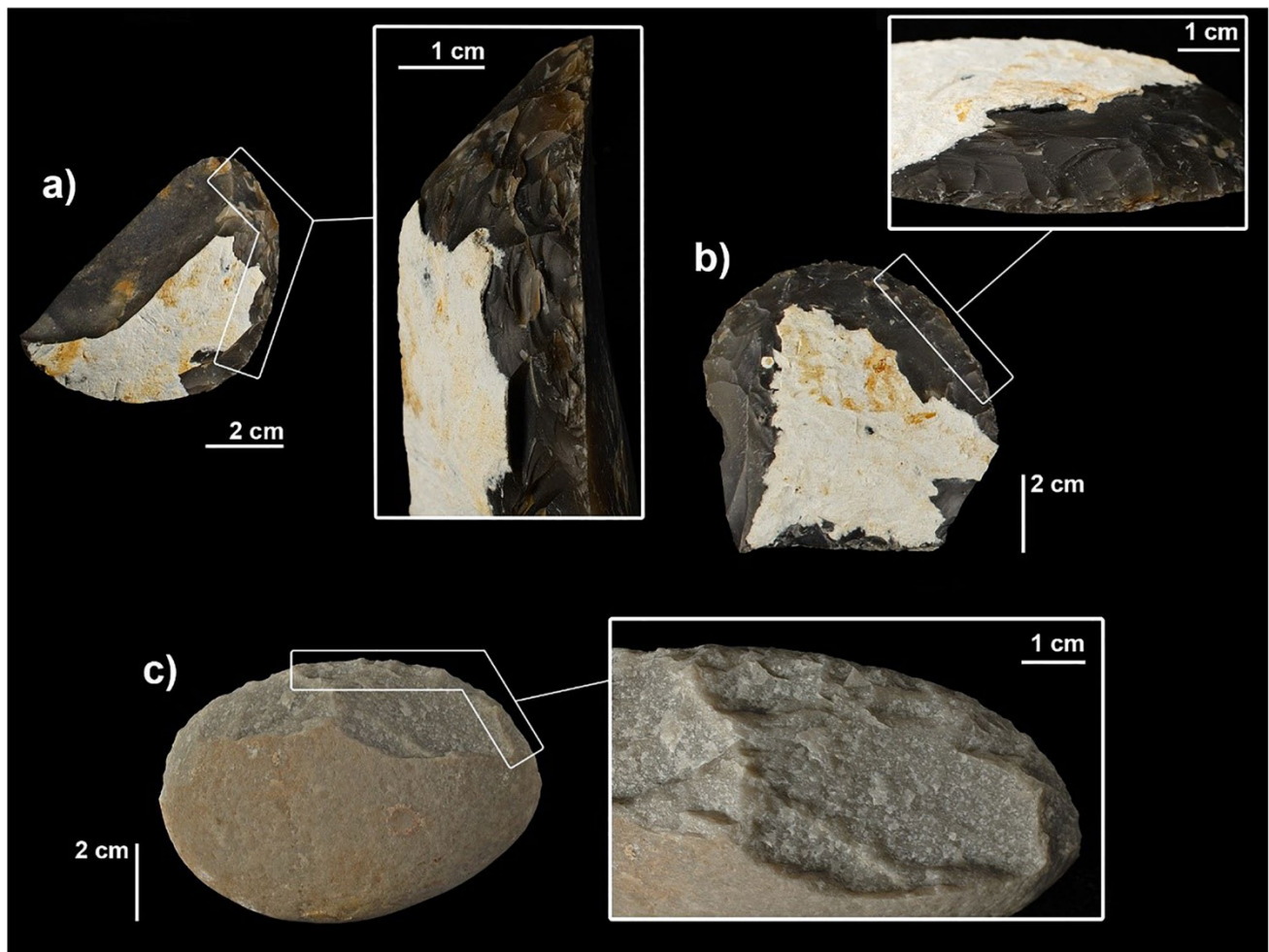


**Fig. 2** Photos to exemplify the gestures and grips used by the experimenters to knap different tools. **a)** UHTR3: knapping a scraper with the piece supported on the leg and using the lingual surface of the tooth; **b)** LHTR7: knapping a Solutrean point with a lower premolar; **c)** IHTR1: knapping a scraper with the labial surface of an incisor and gripping the distal end of the tooth root with three fingers; **d)** UHTR12: knapping a scraper with the mesial surface of an upper molar and gripping most of the tooth with the hand. The hand

that grips the piece is supported by the leg, allowing a wide range of movement during retouching; **e)** UHTR19: knapping a pointed scraper with an upper molar, gripping the tooth with all the fingers covering most of it and enabling a modified power grip; **f)** knapping a scraper with a lower premolar, showing a gesture similar to that shown in **d)**, with the difference being that only three fingers are gripping the tooth root, allowing a precision pinch grip

**Fig. 3** Examples of different types of knapped tools. **a)** A pointed scraper in FN; **b–c)** scrapers in FN; **d)** a Quina scraper in FN; **e)** a denticulate in FN; **f)** bladelets in FN; **g)** backed points in FN; **h)** a Solutrean point in FN; **i)** a scraper in quartzite; **j)** a denticulate in quartzite; **k)** a scraper in quartz; **l)** a scraper in FEV. Photos by M.D. Guillén (IPHES), modified by C. Micó





**Fig. 4** Detailed examples of retouch types. **a)** Quina-type retouch in FN; **b)** a typical scraper knapped in the experiment, showing retouch with direct orientation, continuous distribution, convex delineation,

long removals, a low angle of removals and a subparallel morphology of removals. **c)** Demi-Quina scraper in quartzite. Photos by M.D. Guillén (IPHES), modified by C. Micó

The quartz only allowed knapping of small-sized tools due to the pebbles' internal fissures. The knapped pieces ( $n = 10$ ) included demi-Quina and Quina scrapers. Only a small number of pieces were knapped from this raw material due to the difficulty of making tools without fracturing the pieces.

Thirteen tools were knapped using FEV. In contrast to the FN pieces, the pieces manufactured from FEV showed different features, most probably due to the hardness of the raw material. The removals were short, and the angles of the removals tended to be abrupt or semi-abrupt.

### Analysis of the use-wear marks

The transparent casts were examined with a stereomicroscope (Zeiss Stemi 2000-C) at the Catalan Institute of Human Paleoecology and Social Evolution (IPHES) in Tarragona, Spain. All tooth surfaces used in the experiment were examined under transmitted light. Different

magnifications were used depending on the size of the use-wear traces, from  $6.5\times$  to  $50\times$  magnification. Microphotographs were taken using this same equipment. The alterations were analysed both quantitatively and qualitatively.

Different classifications of use traces on bone have previously been proposed (Rigaud 1977; Vincent 1993; Ahern et al. 2004; Rosell et al. 2011; Mallye et al. 2012; Mozota 2013; Daujeard et al. 2014, 2018); however, some similar use traces have been named differently, making it necessary to establish a consensus on their nomenclature. Here, we opted for the nomenclature established by Mallye et al. (2012) and to differentiate 'discrete active areas' and 'use areas' as a consequence of the superposition of traces produced by the intensive use of a retoucher.

The discrete active areas are as follows:

- **Striations/scores.** These were proposed by Mallye et al. (2012) and defined as 'more or less deep incisions pro-

duced by the edge of the stone flake; they have different forms (rectilinear, sinuous, smooth or rough) and their interior surfaces can be smooth or rough'. They are equivalent to *longitudinaux* (Rigaud 1977) and *hachures* and *entailles* (Vincent 1993) traits; shallow and deep striations (Rosell et al. 2011); linear impressions (Mozota 2013); and hash marks (or hatchings) and grooves (Daujeard et al. 2014).

- **Pits.** These were proposed by Mallye et al. (2012), who defined these as 'deep, with a negative trihedral shape, and are produced by the impact of an apex of the lithic edge against the bone'. They can be triangular or ovoid. They are equivalent to cups (Vincent 1993), grooves (Rosell et al. 2011), trihedral impressions (Mozota 2013) and cupules or chatter marks (Daujeard et al. 2014).

The use areas, proposed by Mallye et al. (2012), are as follows:

- **Hatched areas.** These are created by the superposition of scores on the surface of the bone. They are equivalent to cups (Rigaud 1977) and massive chipping (Mozota 2013).
- **Pitted areas.** These are created by the superposition of pits on the surface of the bone.
- **Scaled areas.** These are created by the superficial detachment of small bone plaques.

## Statistical analysis

Statistical analysis was conducted using R (v.4.2.1) and RStudio software. A chi-square test of independence was applied to determine if the categorical variables were related. A correspondence analysis (CA) was then conducted to visualise the association between the 'retouched raw material' and 'features of use-wear traces' variables. The CA is an extension of a principal component analysis that provides a solution for summarising and visualising datasets in two-dimension plots, and it is a geometric approach used for visualising the rows and columns of a two-way contingency table as points in a low-dimensional space, such that the positions of the row and column points are consistent with their associations in the table (Kassambara 2017). The aim is to identify the morphology of the use-wear traces in accordance with the knapped retouched raw material.

## Results: description of the resulting use-wear traces

In both the upper and lower premolars/molars, the mesial surface of the teeth was the most commonly used part for the knappers to retouch. The active area was the first third of the mesial surface; thus, use-wear traces tended to be found on the part closest to the occlusal surface (Table 2). Four

alterations were in the central area of the mesial surface. The occlusal surface was not effective for knapping. The use of this part of the tooth caused detachment of the enamel and dentine. Regarding the incisors, the active area was the labial surface; thus, the convex surfaces were the most ergonomic active areas for knapping.

Hatched areas were the most common use areas and were identified in 51 (78.45%) of the 65 moulds analysed (including all the processes recorded). Scaled areas appeared in 35 (53.85%) of the total moulds, and pitted areas in 24 (36.92%; Table 2, Fig. 5). However, in the first knapping (t1; recorded for one tool) and the tools that were retouched (pointed scrapers, scrapers, demi-Quina scrapers and Quina scrapers), hatched areas appeared in 27 (84.37%) of the 31 moulds analysed, scaled areas in 8 (25%) and pitted areas in 13 (40.62%). It could be seen that the frequencies remained similar, except for in the scaled areas.

Scaled areas have typically been associated with bone with an intermediate level of freshness and are rare on fresh bone (e.g. Mallye et al. 2012; Rosell et al. 2018). In this experiment, most tooth samples were used in a fresh state, although compared to bone, scaled areas were relatively frequent. This occurrence may be due to tooth structure more than its state of freshness. Teeth consist of layers with different chemical compositions. In horse teeth, cementum comprises the outermost layer, followed by enamel, dentine and enamel again. During knapping, detachment of the layers occurred frequently, which was the reason for the frequent presence of scaled areas (Figs. 5d and 6a–b). On the teeth that were used to make one tool by direct percussion, scaled areas were present 2/10 times on FN, 3/9 on FEV, 5/8 on quartzite and 2/4 on quartz.

The hatched areas (Fig. 6c) correlated with the retouching of flint flakes (chi-square cal: 14.37;  $P < 0.05$ ). Previous works have shown similar results with bone (Mallye et al. 2012). Regarding the teeth that were used to make one tool by direct percussion, hatched areas were present on FN (10/10), FEV (9/9), quartzite (6/8) and quartz (2/2).

Pitted areas were the rarest type of use area. While it is true that they were more common with non-flint raw materials, they could not be correlated with the type of raw material ( $P > 0.05$ ). They were present on FEV (3/9), quartzite (5/8) and quartz (2/4) but not on FN (0/10). Pitted areas on bones have been associated with retouching quartzite flakes (Mallye et al. 2012).

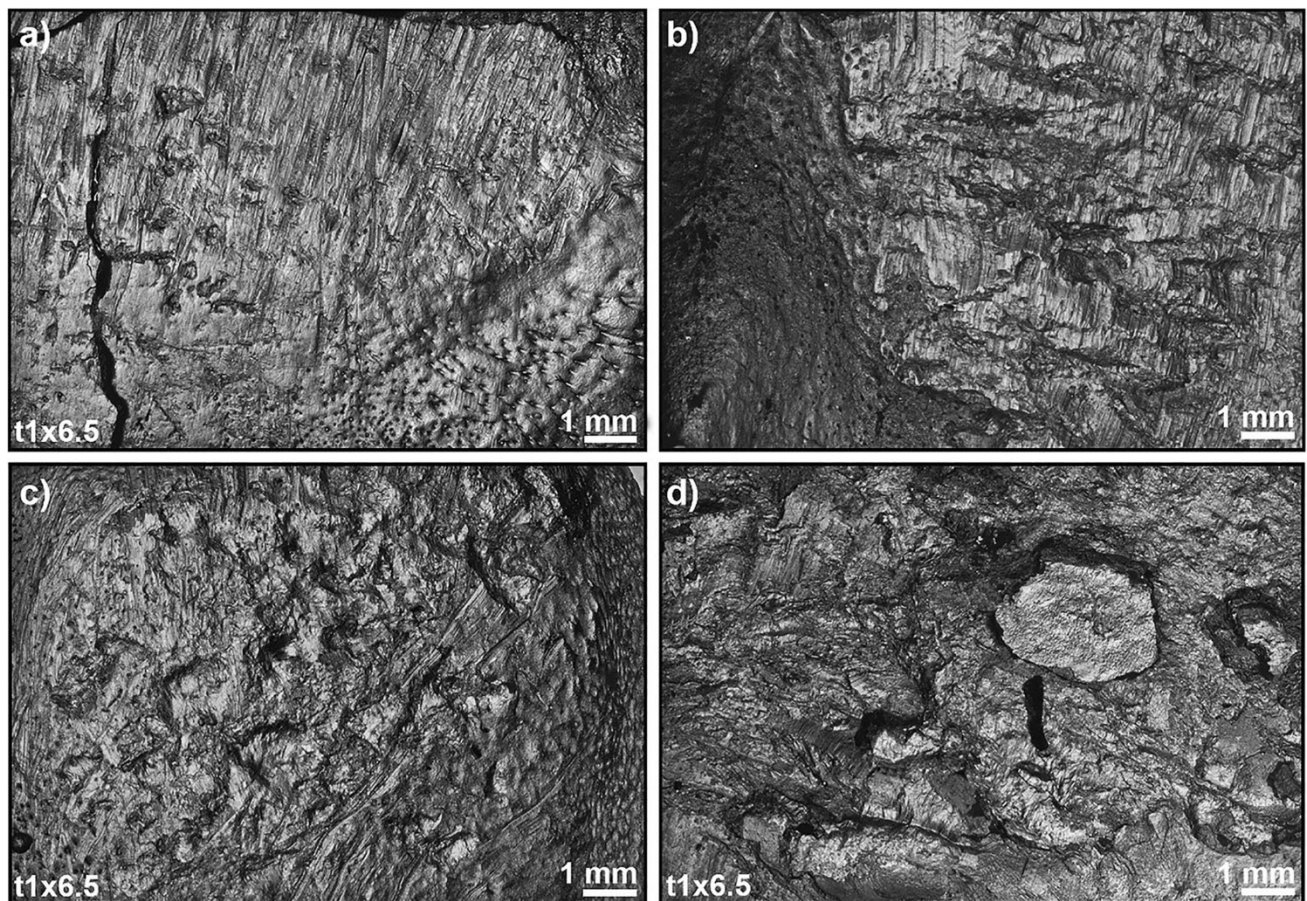
With regard to the discrete active areas, ovoid pits were more common than triangular pits. The former appeared on 44 of the 65 moulds (67%), and the latter on 28 (43%). For the teeth that were used to apply direct percussion, triangular pits appear in 13 of the 31 (42%) moulds, and ovoid pits in 21 (67.7%). The triangular pits were correlated with the retouch of flint flakes (chi-square cal: 16.01;  $P < 0.05$ ). They were present on FN (9/10), FEV (3/9) and

**Table 2** Inventory and interpretative results for the experimental horse tooth retouchers, including: the item's label (ID\_Item), location of use areas (Oc: occlusal; Cent: central; Lat: lateral); type of active areas (Hat: hatched; Pit: pitted; Scal: scaled); type of pits (Tr: triangular; Ov: ovoid); distribution of pits (Iso: isolated; Disp: dispersed; Conc: concentrated); morphology of scores (Rect: rectilinear; Sin: sinuous); side morphology of pits (Sm: smooth; Ro: rough), distribution of scores (Iso: isolated; Disp: dispersed; Conc: concentrated), and the technique utilized depending on whether it served as a retoucher by percussion (RP), by pressure (Press) or by direct percussion (DP)

| ID_Item   | Use active area |                | Discrete active area |           |           |            |       |       | Knapping technique |
|-----------|-----------------|----------------|----------------------|-----------|-----------|------------|-------|-------|--------------------|
|           | Location        | Type           | Pits                 |           | Scores    |            |       |       |                    |
|           |                 |                | Type                 | Dist      | Morph     | Side Morph | Distr |       |                    |
| LHTR1_t1  | Oc              | Pit, Scal      | Ov                   | Iso       | Sin       | Ro         | Conc  | RP    |                    |
| LHTR2_t1  | Oc              | Hat            | Tr, Ov               | Disp, Iso | Rect      | Sm         | Iso   | RP    |                    |
| LHTR2_t2  | Oc              | Pit, Scal      |                      |           |           |            |       | RP    |                    |
| LHTR3_t1  | Oc              | Hat, Scal      | Tr, Ov               | Iso, Iso  | Rect      | Sm         | Iso   | RP    |                    |
| LHTR4_t1  | Oc              | Hat            |                      |           |           |            |       | RP    |                    |
| LHTR4_t2  | Oc              | Hat, Scal      | Tr                   | Iso       | Rect      | Sm, Ro     | Iso   |       |                    |
| LHTR5_t1  | Cent            | Hat            | Tr                   | Iso       | Rect      | Sm, Ro     | Disp  | RP    |                    |
| LHTR6_t1  | Oc, Cent        | Hat            | Tr, Ov               | Iso, Disp | Sin       | Ro         | Disp  | DP    |                    |
| LHTR7_t1  | Oc              | Pit, Scal      | Tr, Ov               | Iso, Iso  | Rect      | Sm         | Conc  | DP    |                    |
| UHTR1_t1  | Cent            | Hat, Pit       | Ov                   | Iso       | Rect      | Sm         | Conc  | Press |                    |
| UHTR2_t1  | Oc              | Hat            | Tr, Ov               | Iso, Iso  | Rect, Sin | Sm, Ro     | Disp  | RP    |                    |
| UHTR2_t2  | Oc              | Hat            | Ov                   | Iso       | Rect      | Sm, Ro     | Disp  |       |                    |
| UHTR3_t1  | Oc              | Hat            | Ov                   | Disp      | Rect      | Sm         | Iso   | RP    |                    |
| UHTR3_t2  | Oc              | Hat            | Ov                   | Disp      | Rect      | Sm         | Iso   |       |                    |
| UHTR4_t1  | Cent            | Hat, Pit, Scal | Ov                   | Iso       | Sin       | Ro         | Iso   | RP    |                    |
| UHTR5_t1  | Oc              | Pit, Scal      | Tr                   | Iso       | Rect      | Sm         | Disp  | RP    |                    |
| UHTR5_t2  | Oc              | Hat, Pit, Scal | Tr                   | Iso       | Rect      | Sm         | Disp  |       |                    |
| UHTR6_t1  | Oc              | Pit, Scal      | Ov                   | Iso       | Rect      | Sm         | Iso   | RP    |                    |
| LHTR8_t1  | Oc              | Hat            | Tr, Ov               |           | Rect      | Sm         | Disp  | RP    |                    |
| LHTR8_t2  | Oc              | Hat            | Tr, Ov               | Iso, Iso  | Rect      | Sm         | Conc  |       |                    |
| LHTR8_t3  | Oc              | Hat            | Tr, Ov               | Iso, Iso  | Rect      | Sm         | Conc  |       |                    |
| LHTR9_t1  | Oc, Cent        | Hat, Scal      | Ov                   | Disp      | Sin       | Ro         | Disp  | RP    |                    |
| LHTR9_t2  | Oc, Cent        | Hat, Scal      | Ov                   | Disp      | Sin       | Ro         | Disp  |       |                    |
| LHTR9_t3  | Oc, Cent        | Hat, Pit, Scal | Tr, Ov               | Iso, Disp | Sin       | Ro         | Disp  |       |                    |
| LHTR10_t1 | Oc              | Hat, Pit       | Ov                   | Iso       | Rect, Sin | Ro         | Disp  | RP    |                    |
| LHTR10_t2 | Oc              | Pit, Scal      | Ov                   | Disp      | Rect, Sin | Ro         | Disp  |       |                    |
| LHTR10_t3 | Oc              | Pit, Scal      | Ov                   | Disp      | Rect, Sin | Ro         | Disp  |       |                    |
| LHTR11_t1 | Oc              | Pit            | Ov                   | Disp      | Sin       | Ro         | Conc  | RP    |                    |
| LHTR12_t1 | Oc              | Hat            | Tr, Ov               | Iso, Iso  | Rect      | Sm, Ro     | Disp  | RP    |                    |
| LHTR12_t2 | Oc              | Hat, Scal      | Tr, Ov               | Iso, Iso  | Rect      | Sm, Ro     | Disp  |       |                    |
| LHTR12_t3 | Oc              | Hat, Scal      | Tr, Ov               | Iso, Disp | Rect      | Sm, Ro     | Disp  |       |                    |
| LHTR13_t1 | Oc              | Hat            |                      |           | Rect      | Sm         | Iso   | RP    |                    |
| LHTR13_t2 | Oc              | Hat, Scal      | Ov                   | Iso       | Rect      | Sm         | Disp  |       |                    |
| LHTR13_t3 | Oc              | Hat, Scal      | Ov                   | Iso       | Rect      | Sm         | Disp  |       |                    |
| UHTR7_t1  | Oc              | Pit            | Ov                   | Disp      | Rect, Sin | Sm, Ro     | Disp  | DP    |                    |
| UHTR8_t1  | Oc              | Hat, Scal      | Tr                   | Iso       | Rect, Sin | Sm, Ro     | Iso   | RP    |                    |
| UHTR9_t1  | Oc              | Scal           |                      |           | Sin       | Ro         | Disp  |       |                    |
| UHTR9_t2  | Oc              | Pit, Scal      | Ov                   | Disp      | Sin       | Ro         | Iso   |       |                    |
| UHTR9_t3  | Oc              | Pit, Scal      | Ov                   | Disp      | Sin       | Ro         | Iso   |       |                    |
| UHTR9_t4  | Oc              | Pit, Scal      | Ov                   | Disp      | Sin       | Ro         | Iso   |       |                    |
| UHTR10_t1 | Oc              | Hat            | Tr                   | Iso       | Rect, Sin | Sm, Ro     | Conc  | RP    |                    |
| UHTR11_t1 | Oc              | Pit, Scal      | Ov                   | Iso       | Sin       | Ro         | Disp  | RP    |                    |
| UHTR12_t1 | Oc              | Hat, Scal      | Tr                   | Iso       |           |            |       | RP    |                    |
| UHTR12_t2 | Oc              | Hat, Scal      | Tr, Ov               | Iso, Iso  | Rect      | Sm         | Conc  |       |                    |
| UHTR12_t3 | Oc              | Hat, Scal      | Tr, Ov               | Iso, Iso  | Rect, Sin | Sm, Ro     | Disp  |       |                    |
| UHTR13_t1 | Oc              | Hat, Pit, Scal |                      |           | Rect, Sin | Ro         | Disp  | RP    |                    |
| UHTR13_t2 | Oc              | Hat, Pit, Scal | Ov                   | Iso       | Rect, Sin | Ro         | Disp  |       |                    |
| IHTR1_t1  | Oc              | Hat            |                      |           |           |            |       | RP    |                    |

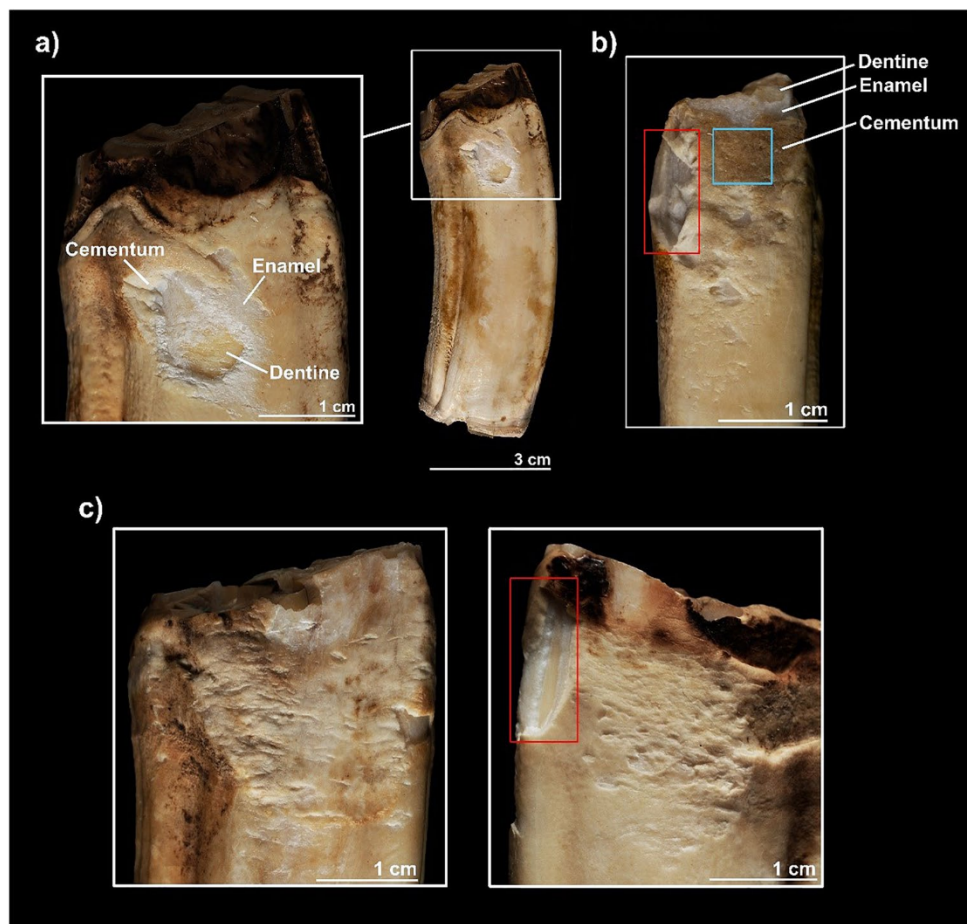
**Table 2** (continued)

| ID_Item   | Use active area |                | Discrete active area |           |           |            |       | Knapping technique |
|-----------|-----------------|----------------|----------------------|-----------|-----------|------------|-------|--------------------|
|           | Location        | Type           | Pits                 |           | Scores    |            |       |                    |
|           |                 |                | Type                 | Dist      | Morph     | Side Morph | Distr |                    |
| IHTR2_t1  | Oc              | Hat, Scal      | Ov                   | Iso       | Rect      | Sm, Ro     | Disp  | RP                 |
| UHTR14_t1 | Oc              | Hat            |                      |           | Rect      | Ro         | Disp  | RP                 |
| UHTR14_t2 | Oc              | Hat            | Tr                   | Iso       | Rect, Sin | Sm, Ro     | Disp  |                    |
| UHTR15_t1 | Oc              | Scal           |                      |           | Sin       | Ro         | Iso   | RP                 |
| UHTR17_t1 | Oc              | Hat, Scal      | Ov                   | Iso       | Sin       | Ro         | Iso   | RP                 |
| IHTR3_t1  | Oc              | Hat, Pit       |                      |           | Rect      | Sm         | Disp  | RP                 |
| UHTR19_t1 | Oc              | Hat            |                      |           | Sin       | Ro         | Iso   | RP                 |
| LHTR14_t1 | Oc              | Hat            | Tr                   | Iso       | Sin       | Ro         | Iso   | RP                 |
| LHTR15_t1 | Cent            | Hat            | Tr, Ov               | Iso, Disp | Rect, Sin | Sm, Ro     | Disp  | RP                 |
| LHTR15_t2 | Oc, Cent        | Hat            | Tr, Ov               | Iso, Disp | Sin       | Sm         | Iso   |                    |
| UHTR20_t1 | Oc              | Hat            | Tr                   | Iso       | Rect      | Sm         | Disp  | RP                 |
| UHTR21_t1 | Oc              | Hat, Scal      | Ov                   | Iso       | Rect, Sin | Ro         | Disp  | RP                 |
| UHTR22_t1 | Cent, Oc, Lat   | Hat            | Tr, Ov               | Iso, Iso  | Rect      | Sm         | Iso   | RP                 |
| UHTR22_t2 | Cent, Oc, Lat   | Hat            | Tr, Ov               | Iso, Iso  | Rect      | Sm         | Disp  |                    |
| UHTR23_t1 | Oc              | Hat, Pit       | Ov                   | Disp      | Sin       | Ro         | Disp  | RP                 |
| UHTR23_t2 | Oc              | Hat, Pit, Scal | Ov                   | Disp      | Sin       | Ro         | Disp  |                    |
| UHTR23_t3 | Oc              | Hat, Pit, Scal | Ov                   | Iso       | Sin       | Ro         | Disp  |                    |



**Fig. 5** Examples of use areas in high-resolution. **a)** UHTR5: slightly pitted area with associated micro-striations; **b)** LHTR15: hatched area; **c)** LHTR11: pitted area; **d)** UHTR9: scaled area

**Fig. 6** Examples of use areas. **a)** UHTR6 shows a characteristic scaled area in which the different layers that form the tooth are exposed after knapping. This tooth was used to knap a Quina scraper on a quartz flake; **b)** LHTR7 shows a scaled area. The red rectangle identifies a typical detachment of the tooth material produced during knapping in the contiguous surface that was used as an active area. The blue square identifies a pitted area that is observable in high-resolution (Fig. 5c). This tooth was used to knap the Solutrean point on an FN flake; **c)** UHTR14 (left) and UHTR2 (right) show typical hatched areas. The former was used to knap two pointed scrapers on FEV flint, and the latter to knap three scrapers on FN flint. The red rectangle identifies a typical detachment of the tooth material produced during knapping in the contiguous surface that was used as an active area. Photos by M.D. Guillén (IPHES), modified by C. Micó



quartz (1/4) but not on quartzite (0/8). Regarding the ovoid pits, there was no correlation with the type of raw material retouched ( $P > 0.05$ ). Although they were more common on non-flint raw materials, they were present on FN (6/10), FEV (4/9), quartzite (8/8) and quartz (3/4). On bone, triangular pits have been associated with the retouch of flint flakes, and ovoid pits with the retouch of quartzite flakes (Mallye et al. 2012).

Sinuuous scores (Fig. 7a) appeared on 37 of the 65 moulds (57%), and rectilinear scores on 41 (63%). For the teeth that were used to make one tool by direct percussion, sinuous scores appeared on 14 (45%) of the 31 moulds, and rectilinear scores on 20 (64%). Sinuous scores were correlated with the retouch of quartzite flakes (chi-square cal: 8.9;  $P < 0.05$ ). They were present on FN (3/10), FEV (2/9), quartzite (7/8) and quartz (2/4). Rectilinear scores (Fig. 7b) were correlated with the retouch of flint flakes (chi-square cal: 8.9;  $P < 0.05$ ). They were present on FN (9/10), FEV (6/9), quartzite (3/8) and quartz (2/4). On bone, sinuous scores have been associated with the retouch of quartzite flakes and rectilinear scores with the retouch of flint flakes (Mallye et al. 2012).

Smooth scores (Fig. 7c) appeared in 35 of the 65 moulds (54%), and rough scores (Fig. 7f) in 40 (61%). For the teeth that were used to apply direct percussion, smooth scores appeared in 17 (55%) of the 31 moulds and rectilinear scores in 21 (68%). Smooth scores were correlated with the retouch of flint flakes (chi-square cal: 11.39;  $P < 0.05$ ) and were present in 9/10 of FN, 6/9 of FEV, 1/8 of quartzite and 2/4 of quartz. In contrast, there was no correlation between the variables of 'rough scores' and 'type of raw material retouched' ( $P > 0.05$ ). Rough scores appeared on FN (7/10), FEV (7/9), quartzite (4/8) and quartz (2/4). On bone, rough scores have been associated with the retouch of quartzite flakes and smooth scores to the retouch of flint flakes (Mallye et al. 2012).

Figure 8 summarises the relationships and correlations between the variables, including 1) type of raw material retouched (FN, FEV or quartzite; quartz was excluded in this analysis due to the small sample of retouched flakes), 2) type of use area (hatched, scaled or pitted) and 3) the features shown in the discrete active areas (triangular pits, ovoid pits, rectilinear scores, sinuous scores, smooth scores or rough scores). Thus, flint raw materials can be associated with

hatched areas, rectilinear scores, smooth scores and triangular pits. The latter could only be correlated with FN, rather than FEV, which demonstrates the differences between the physical properties of both types of flint. On the other hand, quartzite was more associated with the presence of scaled areas, ovoid pits and rough and sinuous scores. The presence of pitted areas seems not to be correlated with any of the variables. Most of the cases' qualitative differences can be clearly distinguished in the morphology of the use-wear traces according to the knapped raw material (Fig. 7a–f).

The same scenario was observed in incisors ( $n = 3$ ), and the direct percussion technique was used to retouch the flakes on FEV. The use area resulted in hatched and scaled areas, and detachment of the cementum could be observed clearly. Isolated pits, dispersed rectilinear, and sinuous scores and associated concentrated micro-striations were associated with these use areas. The incisors presented previous trampling marks. In the archaeological record, these taphonomic alterations can be confused with retouching activities. However, in our experiment, micro-striations always showed a diagonal or vertical orientation with respect to the occlusal-root axis, whereas trampling striae tended to have an isotropic orientation, as previous studies have demonstrated (Micó et al. 2023).

With direct percussion, another characteristic feature is the presence of striae and/or wide striae with internal micro-striations. Generally, they are concentrated in and associated with use areas. Two scenarios were observed that can be categorised as follows: 1) striae/micro-striations were limited to appearing in the use area (they did not run along most of the surface of the teeth), there were no striae/micro-striations or the striae were shallow; 2) there were wide and/or deep striae with internal micro-striations that appeared not only in use areas but extend across most of the surface of the teeth. Both situations depended on the gestures of the knapper rather than the raw material, since:

- Scenario 1 was present in 100% of the teeth that were used by KN1;
- Scenario 2 was present in 100% of the teeth that were used by KN2;
- Scenario 1 was present in 60% and scenario 2 in 40% of the cases by KN3;
- Each scenario was present at a 50% case ratio for KN4;
- Each scenario was present at a 50% case ratio for KN5.

Concentrated striae have been referred to in the literature as scraping marks (*e.g.* Martellotta et al. 2020) and were frequently observed on the retoucher's surface, which was always covered by the retouch-induced marks. Scraping actions have been associated with preparing the bone surface by removing the periosteum (*e.g.* Armand and Delagnes 1998; Mallye et al. 2012; Daujeard et al. 2014)

and preparing the edges of the lithic blank (*e.g.* Costamagno et al. 2018). In the context of this experiment, the presence of scraping marks is associated with the second case, since KN2 used the teeth to prepare the tool-edge in order to facilitate retouching. Analysis of the stigmata by high-resolution methods enabled the distinction between shallow striae and deeper and wider striae with internal micro-striations. This made it possible to identify the different gestures and actions of the knappers during retouching. Working with transparent casts with transmitted light proved to be more advantageous than working with opaque surfaces (directly on bone), since the former enabled a better characterisation of the use-wear trace features (Fig. 7g–h).

The tooth that was used with direct percussion to knap three backed points (UHTR5) showed slightly pitted and hatched areas with associated micro-striations as well as triangular pits and rectilinear and smooth scores. The main difference that was observed here was that the use areas were less marked and deep than those associated with making scrapers or demi-Quina scrapers.

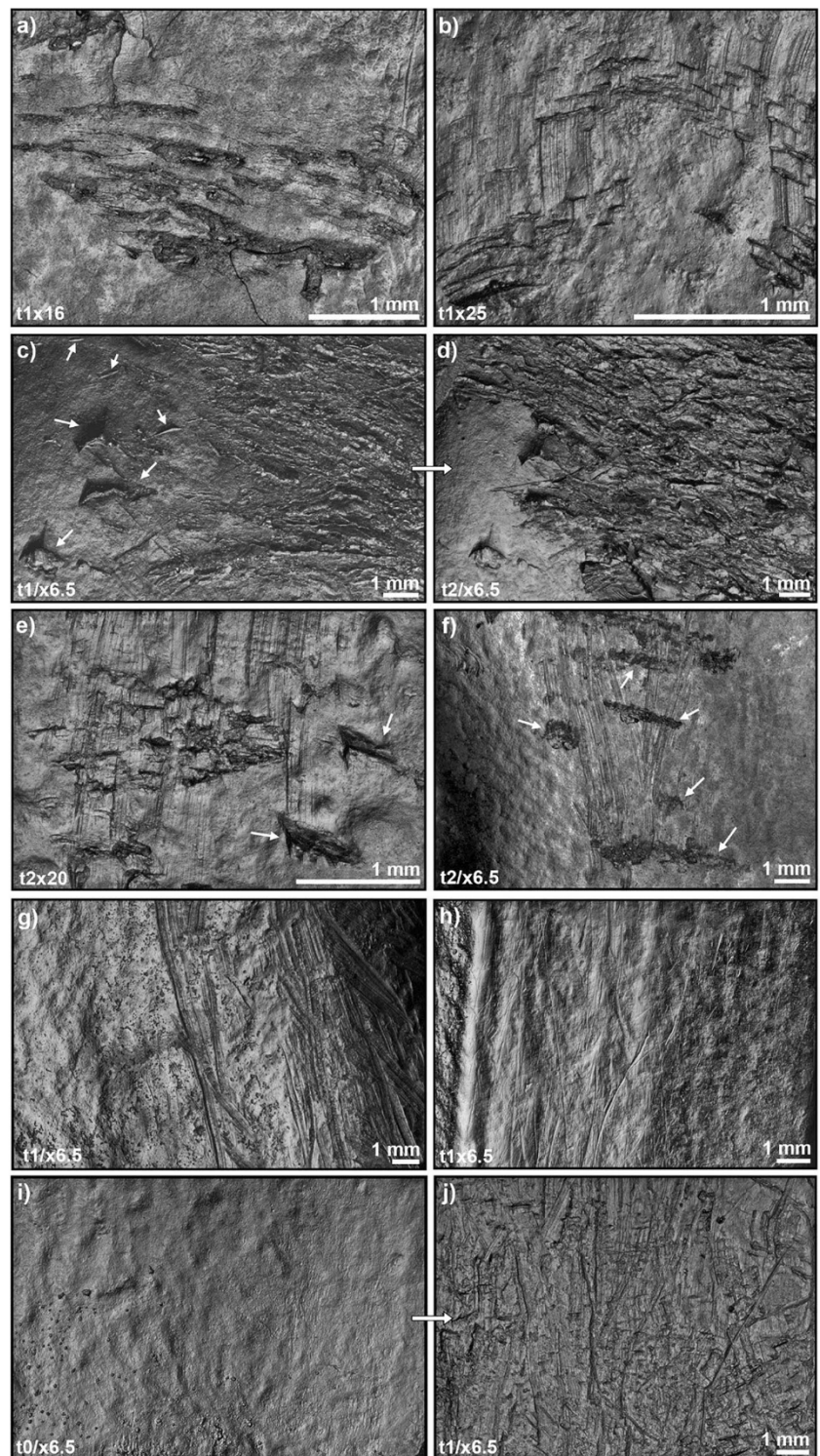
The tooth that was used by direct percussion to knap a small Solutrean point (LHTR7) showed a well-distinguished pitted area as well as scaled areas. The discrete active area was characterised by the presence of rectilinear and smooth scores in a diagonal orientation (around the occlusal-root axis) and the isolated triangular and ovoid pits. The concentrated striae that extended throughout most of the tooth surface and the deep and wide striae with internal micro-striations located below the use area were also notable (Figure S1).

UHTR1 was used to manufacture 10 backed points. The tooth was used as a pressure flaker to retouch bladelets and was gripped between the palm and fingers with pressure placed on the lithic tool edge at the centre of the distal surface (Figure S2). The resulting use-wear traces showed slightly pitted and hatched areas with striae with internal micro-striations, being different to those associated with retouching by percussion (Fig. 7i–j).

Of the teeth, 10/42 showed any type of fracture after the experiment; however, they were still effective for retouching flakes, since the detachments were generally produced in areas contiguous with the use surfaces of the retouchers, whereas the latter remained practically undamaged. In fact, the teeth were useful as hammers for a long time. As an illustration, 10 quartzite flakes were knapped with UHTR9, but despite the hardness of this raw material, the tooth was still effective in retouching subsequent flakes.

The superposition of use-wear traces changed only slightly during the use of the retouchers. The use areas tended to gradually extend from one retouched flake to the next. This way, the features of discrete areas, such as pits or scores, could disappear (Fig. 7c–d). Also, pitted or hatched areas could subsist by extending the scaled areas.

**Fig. 7** **a) h)** LHTR14 after knapping a Quina scraper on FN (t1). Concentrated and sinuous scores with smooth side morphology can be observed. **b)** UHTR8 after knapping a scraper on FN (t1). Concentrated and rectilinear scores with associated striae can be seen. **c)** Microphotograph of UHTR2 after knapping one scraper on FN (t1). The white arrows point to trihedral impressions/pits and rectilinear and smooth scores. The hatched area is also shown in high-resolution. **d)** Microphotograph of UHTR2 after knapping two scrapers on FN (t2) and of the same area as the previous microphotograph. Note how the hatched area extends, causing the disappearance of some pits and scores. **e)** UHTR5 after knapping four backed points on FN (t2). The concentrated rectilinear scores with associated triangular pits and wide and shallow striae with internal micro-striations can be seen. **f)** UHTR13 after retouching two quartzite flakes (t2). White arrows point to shallow and rough pits and rough scores. Note the differences in use-wear features according to the raw material retouch in comparison to the previous microphotographs. **g)** UHTR21 after knapping a demi-Quina scraper (t1). Marked striae with internal micro-striations can be seen. **h)** LHTR7 after knapping a Solutrean point (t1). Concentrated and narrow striae without internal micro-striations can be seen. Note the differences between both types of striae. **g)** UHTR8 after knapping a scraper on FN (t1). Concentrated and rectilinear scores with associated striae can be seen. **h)** LHTR14 after knapping a Quina scraper on FN (t1). Concentrated and sinuous scores with smooth side morphology can be seen. **i)** The natural condition of UHTR1 (t0). **j)** The same tooth after use as a pressure flaker manufacturing 10 backed points. Slightly pitted and hatched areas with associated striae can be seen



## Discussion

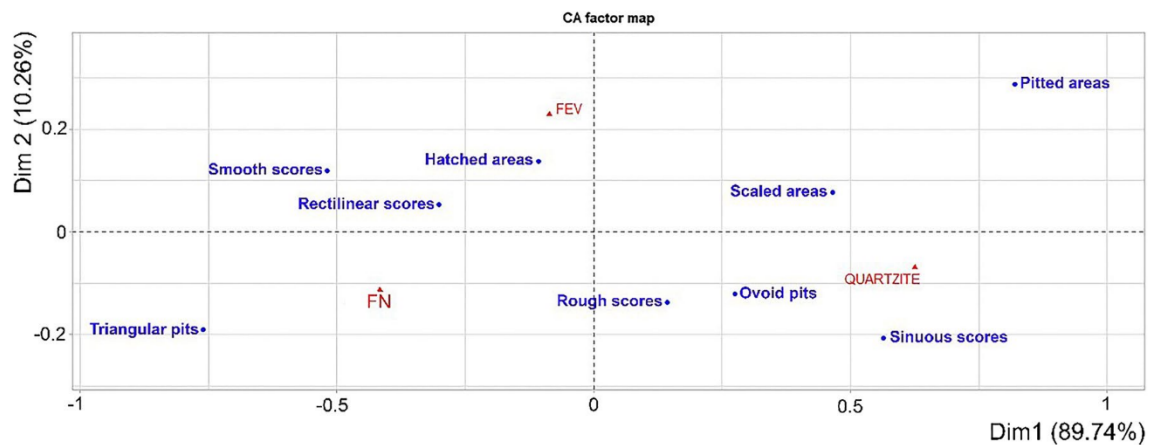
### Bone and teeth: differences

Regarding the morphology of use-wear traces, there were no major differences between bone and teeth; in fact, we found similar results to those of Mallye et al. (2012). The only distinction was that the teeth showed a relative higher frequency of scaled areas than bone (*e.g.* Mallye et al. 2012; Rosell et al. 2018) due to their structure consisting of layers (cementum, enamel, dentine and enamel). We assume more significant differences resulted in the features of the retouch, since horse teeth are heavier and denser than bone. For example, bone retouchers from El Salt (Alicante, Spain) have lengths of between 76 and 135 mm and widths of between 10 and 36 mm (Pérez et al. 2019), and the lengths and widths of those from De Nadale Cave range from 54 to 150 mm and 20 to 46 mm, respectively (Martellotta et al. 2020). Although the length of horse teeth can vary depending on the ontogenic age of the individual, their sizes are similar to those of bone retouchers, but they are heavier due to their chemical composition. Thus, retouching with teeth may facilitate the manufacture of certain types of tools, especially those made from thick flakes, such as demi-Quina or Quina scrapers. Nevertheless, comparisons between the key features of retouchers and retouched tools rarely seem to be considered in the literature (*e.g.* Costamagno et al. 2018). This gap could be due to factors such as the recovery of inadequate samples of bone retouchers for use in association with a lithic sample in terms of the number of finds or their preservation state (Martellotta et al. 2020). In any case, this experimental work demonstrated the flexibility of horse teeth in the manufacture of a wide range of tools using Middle and Upper Palaeolithic knapping techniques.

### Horse tooth retouchers in the archaeological record

Horse tooth retouchers have been found in various Middle and Upper Palaeolithic sites (Table 3), including La Ferrassie (Savignac-de-Miremont, Dordogne, France; Castel et al. 2003), Laugerie-Haute (Les-Eyzies-de-Tayac, Dordogne, France; Castel and Madelaine 2006), La Quina (Gardes-le-Pontaroux, Charente, France; Verna and d'Errico 2011), Gough's Cave (Cheddar, Somerset, UK; Bello and Galway-Witham 2019; Bello et al. 2021), Chez-Pinaud (Jonzac, Charente-Maritime, France; Rendu et al. 2023), Trou de l'Abîme (Couvin, Namur, Belgium; Abrams and Cattelain 2014), Trou Magrite (Pont-à-Lesse, Namur, Belgium; Abrams 2023), and Trou du Diable (Hastièrre-Lavaux, Namur, Belgium; Abrams 2023).

Bello and Galway-Witham (2019) and Bello et al. (2021) provided a detailed description of the morphology of the use-wear traces of an upper third molar (M50064) and an incisor (M49811) associated with Magdalenian layers from Gough's Cave; the authors described the molar as follows: 'The surface of the tooth exhibits a plethora of microscopic knapping pits, scores and scratches which mark the enamel on four sides of the tooth [...] intense wear is concentrated on the flatter (mesial) surface of the molar, near the middle of the crown and towards its base. In these zones, repeated micro-chipping of the enamel has hollowed-out a dish-shaped depression [...] The area of intense attrition on the medial face is associated with flaking that has removed the mesostyle along the lower two-thirds of the tooth' (Bello et al. 2021). The authors suggested that the most probable use of the tooth was as a pressure flaker, although it could have also been used for direct percussion (Bello et al. 2021). In addition, some superficial and parallel scratches in M50064 are associated with the preparation of the margins of the lithic tools before retouching it (Bello et al. 2021). In our experimental work, knapper 2 also performed the preparation of the lithic blank, resulting in wide and/or deep striae with internal micro-striations that appeared not only in use areas but extended across most of the surface of the teeth (*e.g.* UHTR21, Fig. 7g). Both types of marks, those found in M50064 and those found in the teeth of our experiment, are different. In addition, in our experiment, UHTR1 was used to manufacture 10 backed points, simulating the technique of a pressure flaker by gripping the tooth between the palm and fingers and putting pressure on the lithic tool-edge in the centre of the distal surface. The marks on UHTR1 did not share the features of M50064, and the latter seems to have had more intensive use. The results of our experiment suggest that the removal of the mesostyle would have been unlikely through pressure flaking since the retouching of bladelets using this technique did not produce this alteration. Also, M50064 does not show the typical hatched areas associated with retouched flint flakes. On the other hand, it does exhibit the alterations that we refer to in our study as scaled and pitted areas. Bello et al. (2021) describe that this area 'shows minute punctiform features, transverse micro-abrasion and a large depression where the focus of pressure flaking has abraded the enamel to form a bowl-shaped depression'. These features are consistent with the results we obtained in our experiment and support its association with one of the various uses of the tooth as a retoucher. Other alterations illustrated in M50064 are 'random striations' (Bello et al. 2021; Fig. 2J). In Micó et al. (2023), it was demonstrated that trampling can also produce shallow striae with an isotropic distribution. Although it is undeniable that M50064 was used as a tool, the possibility of the



**Fig. 8** Correspondence analysis of the retouched raw material (red) and the type of use area and features of the discrete active areas (blue), according to the nomenclature proposed by Mallye et al. (2012)

presence of taphonomic marks should also be considered. From our perspective, M50064 shows features in the use-wear traces that are consistent with the use of the tooth as a retoucher (scaled and pitted areas), but others such as the removal of the mesostyle or the shallow striae with multiple orientations were not identified in our experimental sample. Based on these considerations, other uses that have not been considered in this study should be experimentally conducted to establish parallels, such as the technique of direct percussion or bipolar percussion using the tooth as an anvil.

Bello et al. (2021) described a horse incisor retoucher (M49811) as follows: ‘Knapping marks are concentrated on the buccal face of the crown and include transverse gouges and angular pits located near the base of the crown and vertically oriented scratches that extend from the gouges towards the incisal surface. The superficial abrasions of the enamel with multiple striations are consistent with a lithic tool-edge sliding across the enamel surface’. Also, M49811 showed a score with scratches and pits (Bello et al. 2021, Fig. 3). These scratches are similar to those obtained by knapper 2 in our experiment when the tooth was used to abrade the lithic blank which produced deep striae with internal micro-striations (e.g. UHTR21, Fig. 7g). Moreover, the score is similar to those obtained by percussion in our experiment (e.g. LHTR14, Fig. 7a). The authors suggested that this tooth was used as a pressure flaker to shape or resharpen a tool edge (Bello et al. 2021). However, based on our experiment, this tooth seems to have been used more to prepare the edge of a lithic blank, and then as a retoucher by percussion. We assume that during knapping, several technical actions are applied, such as using the tooth to abrade the tool-edge of a flake to avoid unintended fractures and the formation of notches in the edge, and after, by direct percussion to shape or resharpen the tool edge. In our experiment, we used three horse incisors to retouch flint flakes by direct percussion

(IHTR1, IHTR2 and IHTR3). They showed typical hatched areas on the labial/buccal surface as well as scaled areas due to the detachment of the cementum (Fig. 9). Hatched areas are created by the superposition of scores on the surface of the bone (Mallye et al. 2012), in this case teeth. Since M49811 only presents one score, and the hatched area has not been formed, we assume a low use of M49811.

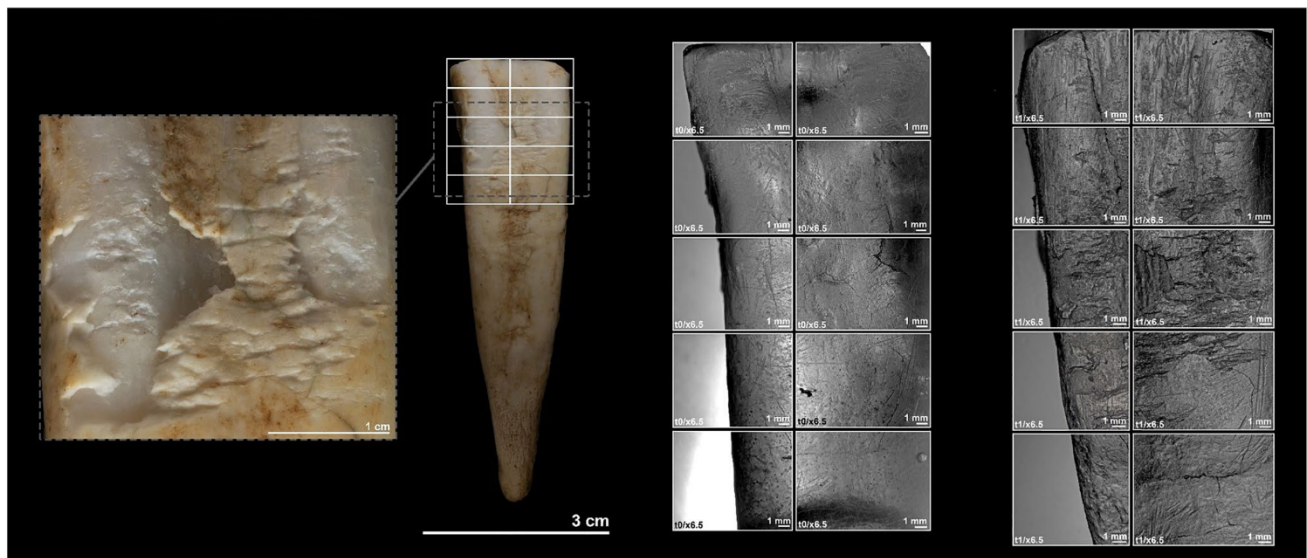
Another horse incisor, from Chez-Pinaud, was recovered from Stratigraphic Unit 22 and attributed to the Quina Moustérien (Rendu et al. 2023). The authors did not provide a detailed description of the features of the use-wear traces; as can be seen in their photograph (Rendu et al. 2023, Fig. 8), the incisor (Piece #4061) showed a characteristic hatched area with associated scraping marks that were on the labial surface and concentrated on the lateral part of the tooth. Piece #4061 did not show as intense use as IHTR2; the results of our experiment showed the presence of isolated, dispersed or concentrated use areas that could be associated not only with the number of blows performed during the retouching of a flake but also with the gestures of the knappers (e.g. the speed of the blows) and the thickness of the flake. IHTR1 and IHTR2 were used by the same knapper employing the same gestures. IHTR1 was used to retouch one flint flake, and IHTR2 to retouch two. Nevertheless, the former showed less concentrated marks than the latter. Regarding IHTR3, which was used by another knapper, this tooth’s resulting marks were almost imperceptible and were only observable using high-resolution methods. Thus, piece #4061 seemed to have been used to retouch a limited number of flakes by direct percussion. Use-wear traces on IHTR1, IHTR2, IHTR3 and piece #4061 showed different features to those of M49811. This fact is also evidence of the use of different techniques using horse teeth during the Middle and Upper Palaeolithic, since they could be identified through the characterisation of the use-wear traces.

**Table 3** Horse tooth retouchers identified in the archaeological site in which was recovered, the surface that was used, features of the use-wear traces described by the authors (N/A: unavailable information in the paper), the associated uses by the authors, the features of the use-wear traces according to this study, and the potential uses according to this study

| Type of tooth    | Site           | Period           | Used surface                    | Features of the use-wear traces                                                                                                                                                            | Associated uses                                                                              | Features of the use-wear traces observed in this study | Potential uses according to this study                            | References                  |
|------------------|----------------|------------------|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|--------------------------------------------------------|-------------------------------------------------------------------|-----------------------------|
| Incisor          | Gough's Cave   | Magdalenian      | Labial, mesial, distal, lingual | Transverse gouges, angular pits, vertical scratches                                                                                                                                        | Pressure flaker or to resharpen a tool edge                                                  | Same observations as the authors                       | Retouching by percussion and to abrade the edge of a lithic blank | Bello et al. (2021)         |
| M <sup>3</sup>   | Gough's Cave   | Magdalenian      | Mesial, distal, buccal, lingual | Pits, scores and scratches. Gouges and chipped enamel Partially removed mesostyle                                                                                                          | Pressure flaker, direct percussion, preparation of margins of lithic tools before retouching | Same observations as the authors                       | Retouching by percussion and other unclear uses                   | Bello et al. (2021)         |
| Incisor          | Chez-Pinaud    | Quina Mousterian | Labial                          | N/A                                                                                                                                                                                        | Retoucher                                                                                    | Hatched areas, pits, striae                            | Retouching by percussion                                          | Rendu et al. (2023)         |
| M <sub>3</sub>   | Laugerie-Haute | Solutrean        | Mesial                          | 'Stries de raclage sub-parallèles. Les entailles de formes allongées, parfois cuneiformes.' Sub-parallel scraping striae. The notches are elongated, sometimes wedge-shaped                | Retoucher                                                                                    | Hatched areas, scaled areas, striae                    | Retouching by percussion                                          | Castel and Madelaine (2006) |
| M <sub>1/2</sub> | Laugerie-Haute | Solutrean        | Mesial                          | 'Stries de raclage sub-parallèles. Stries verticales isolées. Stries de direction mésiodistale.' Sub-parallel scraping striae. Isolated vertical striae. Striae in a mesiodistal direction | Retoucher                                                                                    | Hatched areas, scaled areas, striae                    | Retouching by percussion                                          | Castel and Madelaine (2006) |

Table 3 (continued)

| Type of tooth         | Site            | Period           | Used surface     | Features of the use-wear traces                                                                                                                                                                      | Associated uses            | Features of the use-wear traces observed in this study | Potential uses according to this study | References                 |
|-----------------------|-----------------|------------------|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|--------------------------------------------------------|----------------------------------------|----------------------------|
| M <sup>1/2</sup>      | La Ferrassie    | Aurignacian      | Mesial           | 'Dépressions profondes, larges et irrégulières. Stries rectilignes, régulières, à section en 'V',<br>Deep, wide, and irregular depressions. Straight, regular striae with a 'V'-shaped cross-section | Pressure flaker, retoucher | Hatched areas, scaled areas                            | Unclear                                | (Castel et al. 2003)       |
| Pm <sub>1/2</sub>     | La Ferrassie    | Aurignacian      | Mesial           | 'Dépressions profondes, larges et irrégulières. Stries rectilignes, régulières, à section en 'V',<br>Deep, wide, and irregular depressions. Straight, regular striae with a 'V'-shaped cross-section | Retoucher                  | Unclear                                                | Unclear                                | (Castel et al. 2003)       |
| Lower molar/pre-molar | La Quina        | Quina Mousterian | Buccal           | N/A                                                                                                                                                                                                  | Retoucher                  | Hatched areas, striae and pits                         | Retouching by percussion               | Verna and d'Errico (2011)  |
| Upper molar/pre-molar | Trou de l'Abîme | Mousterian       | Mesial or distal | N/A                                                                                                                                                                                                  | Retoucher                  | Unclear                                                | Unclear                                | Abrams and Catelain (2014) |
| Upper molar/pre-molar | Trou de l'Abîme | Mousterian       | Mesial or distal | N/A                                                                                                                                                                                                  | Retoucher                  | Hatched areas, scaled areas, scores, striae            | Unclear                                | Abrams and Catelain (2014) |
| Upper molar/pre-molar | Trou Magrite    | Decontextualized | Mesial or distal | N/A                                                                                                                                                                                                  | Retoucher                  | Unclear                                                | Unclear                                | Abrams (2023)              |
| Upper molar/pre-molar | Trou du Diable  | Decontextualized | Mesial or distal | N/A                                                                                                                                                                                                  | Retoucher                  | Hatched area                                           | Retouching by percussion               | Abrams (2023)              |



**Fig. 9** IHTR2, showing typical hatched areas produced by retouched flint. The tooth also shows scaled areas as a consequence of the detachment of the cementum. Microphotographs on the left show the initial condition (t0) before the tooth had been used for the experiment. Note the presence of trampling marks. Microphotographs on

the right show the use-wear traces produced after the experiment. Such traces are also characterised by the presence of isolated ovoid pits and smooth and rough rectilinear scores. The tooth was used to knap a scraper on FEV. Photos by M.D. Guillén (IPHES), modified by C. Micó

Two more notable horse molars described by Castel and Madelaine (2006) are associated with Solutrean horizons from Laugerie-Haute. These teeth show hatched and scaled areas on the mesial surface that are identical to those that resulted from our experiment using direct percussion. Castel and Madelaine (2006) provided an approximation of the teeth's use of between 30 and 50 blows. They also suggested that 1) this type of material could have been overlooked in the archaeological record, and 2) following the identification of Solutrean horse tooth retouchers in Laugerie-Haute, the existence of similar tools belonging to other Upper Palaeolithic cultures should be considered. Nowadays, they are known in Middle Palaeolithic contexts. We too suggest paying attention to these pieces, since use-wear traces on some pieces were almost imperceptible (IHT3, LHTR6, UHTR1, UHTR5, UHTR19, UHTR20 and UHTR22; Figures S3, S4 and S5) and were only observable using high-resolution methods, based on our experiment.

From couche F (Aurignacian I) from La Ferrassie, six teeth are considered retouchers (Castel et al. 2003): a *Panthera spelae* upper left canine (B.435.1); a *Panthera spelae* lower right canine (B.435.3); a *Panthera spelae* upper right or left canine (B.435.5); an *Equus ferus* upper molar, right 1 or 2 (the nomenclature is not mentioned), and an *Equus ferus* lower premolar, left 3 or 4 (the nomenclature is not mentioned). Castel et al. (2003) describe a horse upper right molar as showing a series of fine horizontal incisions (the tooth being in anatomical position) and associated with small detachments. These marks appear to correspond more to pressure than to

gestures made from percussion and are located on the mesial surface of the tooth (Castel et al. 2003). The lower premolar is more uncertain, and exhibits similar but fewer marks, mainly associated with polyhedral and oblique detachments on the base of the crown, which could be traces of carnivore toothmarks (Castel et al. 2003). A comparison of these horse teeth with the results of our experiment is unfeasible because the features of the use-wear traces cannot be clearly discerned from the figures (Castel et al. 2003, Fig. 2). Regarding carnivore canines, numerous areas are evident on all the surfaces (e.g. Castel et al. 2003, Fig. 4), featuring hatched and pitted areas like those obtained in our experiment when the teeth were used as retouchers by percussion.

Trench L from la Quina mentions a lower premolar/molar which shows hatched areas, scores, and some striae (Verna and d'Errico 2011, Fig. 11). These marks resemble those obtained in our experiment (e.g. UHTR14 and UHTR2, Fig. 6c; LHTR14 and UHTR8, Fig. 7a-b), indicating that their use is consistent as a percussion retoucher.

Horse upper molars or premolars have also been documented as retoucher in a few sites from Belgium: Trou Magrite, Trou du Diable and Trou de l'Abîme (Abrams and Cattelain 2014; Abrams 2023). Nevertheless, the only site that has yielded a chrono-cultural attribution to the teeth is Trou de l'Abîme, being framed within the Moustertian, MIS3 (Abrams and Cattelain 2014; Abrams 2023). Two horse tooth retouchers are mentioned by Abrams and Cattelain (2014) from Trou de l'Abîme although there is no description of the use-wear traces. A comparison with

the results of our experiment is complicated in one of the teeth since the surface of the active area is covered by root etchings (Abrams and Cattelain 2014, Fig 10). The other horse tooth retoucher shows hatched and scaled areas, scores, and striae (Abrams and Cattelain 2014, Fig 10); thus, it is consistent with use as retoucher by percussion.

In light of these considerations, horse teeth seem to have been used to perform different technical actions during the Middle and Upper Palaeolithic. In our view, tooth retouchers from the Mousterian, Aurignacian and Solutrean contexts show traces that can be associated with similar activities and a similar intensity of use. Moreover, most of them were used employing the mesial surface. In contrast, the teeth from Magdalenian contexts were used by employing their four surfaces and showed a higher intensity of use. However, we suggest they should be analysed more deeply using high-resolution methods to enable comparisons and to better understand how they were used.

## Conclusion

This work provides evidence for the effectiveness of hypodont teeth as retouchers for the manufacture of a wide range of tools. They are well-suited for use with different techniques, such as direct percussion or pressure flaking as well as in the different gestures of knappers. The analysis of the use-wear using high-resolution methods allowed us to do the following:

- 1) Correlate the specific features of the use-wear traces with the type of raw material retouched (flint or quartzite);
- 2) Distinguish the specific features associated with the use of two different retouching techniques (pressure flaking vs direct percussion);
- 3) Distinguish the specific features associated with certain actions realised by the knappers, such as abrasion of the tool edge. The analysis of the use-wear by the construction of transparent casts and the analysis with a stereomicroscope using transmitted light allowed us to distinguish the shallow striae and deeper and wider striae with internal micro-striations;
- 4) Record the superposition of use-wear traces through the moulding of the teeth surfaces in specific steps during the experiment. A more intense use produced an expansion of the use areas. Therefore, specific areas such as scores or pits can overlap;
- 5) Compare them with those produced on bone. Scaled areas are relatively more frequent on teeth and can be associated with tooth structure (cementum, enamel, dentine and enamel);
- 6) Define a framework for comparing horse tooth retouchers from the archaeological record.

The comparison of horse teeth from archaeological sites through the literature review provides a better understanding about the purpose of using teeth as tools by both Neanderthal and early modern populations and sheds light on how these human groups used them. The discussion about their choices and technical abilities leads to the consideration of tooth retouchers as elements within the *chaîne opératoire* in lithic manufacture. Like other authors, we suggest that pieces of this type be carefully analysed because they could go undetected. The fact that, in our experiment, some alterations were occasionally barely distinguishable to the naked eye reinforces this likelihood. Finally, we note the importance of these types of experimental studies to create analogies and identify past processes.

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**Author contribution** CM, FC, RB, and FR conceived/designed the experiment. CM, FC, JLL, PS, and LZ performed the experiment. CM created the microphotographs of the teeth. CM analysed the materials and interpreted the results with contributions from RB and FR. CM wrote the original draft with input from FC, JLL, PS, LZ, FR and RB. All authors contributed to the manuscript and approved the definitive version, and all authors qualifying for authorship are listed.

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**Data availability** Percentages of explained variances of the correspondence analysis (CA; Table S2), examples of macro- and microphotographs of the use-wear traces (Figure S1, S3, S4 and S5) and a snapshot illustrating how UHTR1 was used as a pressure flaker have been included as supplementary files. The interpretative results for the experiment, macro- and microphotographs of all use-wear traces, and all videos of the retouching activities recorded during the experiment

can be downloaded from the Research Data Repository (CORA.RDR) at <https://doi.org/https://doi.org/10.34810/data689>.

## Declarations

We have no conflicts of interests to declare. All authors have read and approved the present study and take full responsibility for its content.

**Competing interests** The authors declare no competing interests.

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## References

- Abrams G, Cattelain P (2014) Le Trou de l'Abîme à Couvin (Prov. Namur, Belgique). Bilan archéozoologique préliminaire de la couche II (fouilles 1984–1987). *Archéo-Situla* 34:33–40
- Abrams G, Bello SM, Di Modica K, Pirson S, Bonjean D (2014) When Neanderthals used cave bear (*Ursus spelaeus*) remains: bone retouchers from unit 5 of Scladina Cave (Belgium). *Quat Int* 326–327:274–287. <https://doi.org/10.1016/j.quaint.2013.10.022>
- Abrams G (2023) Close encounters of the third kind?: Neanderthals and modern humans in Belgium, a bone story. Doctoral Thesis. Leiden University. <https://hdl.handle.net/1887/3618716>
- Ahern JCM, Karavanić I, Paunović M, Janković I, Smith FH (2004) New discoveries and interpretations of hominid fossils and artifacts from Vindija cave. *Croatia J Hum Evol* 46(1):25–65. <https://doi.org/10.1016/j.jhevol.2003.09.010>
- Andrews P (1995) Experiments in taphonomy. *J Archaeol Sci* 22(2):147–153. <https://doi.org/10.1006/jasc.1995.0016>
- Armand D, Delagnes A (1998) Les retouches en os d'Artenac (couche 6c): perspectives archéozoologiques, taphonomiques et expérimentales. In: Brugal, J.-P., Meignen, L., Patou-Mathis, M. (Eds.), *Économie Préhistorique: Les Comportements de Subsistance au Paléolithique. XVIIIe Rencontre Internationale d'Archéologie et d'Histoire d'Antibes*. Éditions APDCA, Sophia Antipolis, 205–214
- Bello S, Galway-Witham J (2019) Bone taphonomy inside and out: Application of 3-dimensional microscopy, scanning electron microscopy and micro-computed tomography to the study of humanly modified faunal assemblages. *Quat Int* 517(20):16–32. <https://doi.org/10.1016/j.quaint.2019.02.035>
- Bello SM, Crété L, Galway-Witham J, Parfitt SA (2021) Knapping tools in Magdalenian contexts: new evidence from Gough's Cave (Somerset, UK). *PLoS ONE* 16(12):e0261031. <https://doi.org/10.1371/journal.pone.0261031>
- Blasco R, Rosell J, Peris JF, Cáceres I, Verges JM (2008) A new element of trampling: an experimental application on the Level XII faunal record of Bolomor Cave (Valencia, Spain). *J Archaeol Sci* 35(6):1605–1618. <https://doi.org/10.1016/j.jas.2007.11.007>
- Boëda E, Vincent A (1990) Rôle plausible de l'os dans la chaîne de production lithique à La Quina: données expérimentales. *Colloque International "Les Moustériens Charentais"* (Brive, La Chapelle-aux-Saints, 26–29 Août 1990), *Résumés des Communications*, 51–52
- Bonnichsen R (1989) Constructing taphonomic models: theory, assumptions, and procedures. In: Bonnichsen, R., Sorg, M. (Eds.), *Bone Modification*. University of Maine: Centre for the Study of the First Americans, Orono, 515–526
- Bordes F (1961) *Typologie du Paléolithique ancien et moyen*. Presses du CNRS, 5e édition, 1988, Paris
- Bourguignon L (2001) Apports de l'expérimentation et de l'analyse techno-morpho fonctionnelle à la reconnaissance de processus d'aménagement de la retouche Quina. In: Bourguignon, L., Frère-Sautot, M.-C. (Eds.), *Préhistoire et Approche Expérimentale, Préhistoire 5*. Éditions Monique Mergoil, Montagnac, 35–66
- Camarós E, Münzel S, Cueto M, Rivals F, Conard N (2016) The evolution of Paleolithic hominin–carnivore interaction written in teeth: Stories from the Swabian Jura (Germany). *J Archaeol Sci Rep* 6:798–809. <https://doi.org/10.1016/j.jasrep.2015.11.010>
- Castel J-C, Madelaine S (2006) Quelques éléments remarquables de la faune du Solutrén de Laugerie-Haute (Les-Eyzies-de-Tayac, Dordogne). *Paléo* 18:275–284
- Castel J-C, Chauvière F-X, Madelaine S (2003) Sur os et sur dents: les "retouchoirs" aurignaciens de la Ferrassie (Savignac de-Miremont, Dordogne). *Paléo* 15:29–50
- Costamagno S, Bourguignon L, Soulier M, Meignen L, Beauval C, Rendu W, Maureille B (2018) Bone retouchers and site function in the Quina Mousterian: The case of Les Pradelles (Marillac-le-Franc, France). In: Hutson, J.M., García Moreno, A., Noack, E.S., Turner, E., Villaluenga, A., Gaudzinski-Windheuser, S. (Eds.), *The Origins of Bone Tool Technologies*. Römisch-Germanisches Zentralmuseum – TAGUNGEN. Verlag des Römisch-Germanischen Zentralmuseums, Band 35, 269–285
- Cuchí O, Mazo C (1992) Sílex y Prehistoria. Análisis mineralógico de muestras síliceas de Huesca y Zaragoza. *Bolskan: Revista de arqueología del Instituto de Estudios Altoaragoneses* 9, 9–50
- Daujeard C, Moncel M-H, Fiore I, Tagliacozzo A, Bindon P, Raynal J-P (2014) Middle Paleolithic bone retouchers in Southeastern France: variability and functionality. *Quatern Int* 326–327:492–518. <https://doi.org/10.1016/j.quaint.2013.12.022>
- Daujeard C, Valensi P, Fiore I, Moigne A-M, Tagliacozzo A, Moncel M-H, Santagata C, Raynal J-P (2018) A reappraisal of Lower to Middle Paleolithic bone retouchers from southeast-ern France (MIS11 to 3). In: Hutson JM, García- Moreno A, Noack ES, Turner E, Villaluenga A, Gaudzinski-Windheuser S (eds) *The Origins of Bone Tool Technologies*. Verlag des Römisch-Germanischen Zentralmuseums, Mainz, pp 93–132
- David E, Pelegrin J (2009) Possible late glacial bone "retouchers" in the Baltic Mesolithic: the contribution of experimental tests with lithics on bone tools. In: Street, M., Barton, N., Terberger, T. (Eds.), *Humans, Environment and Chronology of the Late Glacial of the North European Plain: Proceedings of Workshop 14 (Commission XXXII) of the 15th U.I.S.P.P. Congress*. Lisbon, September 2006. RGZM-Tagungen 6. Verlag des Römisch-Germanischen Zentralmuseums, Mainz, 155–168
- Domínguez-Rodrigo M, De Juana S, Galán AB, Rodríguez M (2009) A new protocol to differentiate trampling marks from butchery cut marks. *J Archaeol Sci* 36(12):2643–2653. <https://doi.org/10.1016/j.jas.2009.07.017>
- Doyon L, Li Z, Li H, d'Errico F (2018) Discovery of circa 115,000-year-old bone retouchers at Lingjing, Henan, China. *Petraglia MD (ed). PLoS One* 13(3), e0194318. <https://doi.org/10.1371/journal.pone.0194318>
- Habibah TU, Amlani DV, Brizuela M (2022) *Hydroxyapatite Dental Material*. StatPearls Publishing, Treasure Island (FL)
- Healy F, Marshal P, Bayliss A, Cook G, Bronk Ramsey C, van der Plicht J, Dunbar E (2018) When and Why? The Chronology and

- Context of Flint Mining at Grime's Graves, Norfolk, England. *Proc Prehist Soc* 84:277–301. <https://doi.org/10.1017/ppr.2018.14>
- Henri-Martin L (1906) Industrie Moustérienne perfectionnée. Station de La Quina (Charente). *Bull Soc Préhist Fr* 3:233–239
- Henri-Martin L (1907) Présentation d'ossements utilisés de l'époque moustérienne. *Bull Soc Préhist Fr* 4:269–277
- Hutson JM, García-Moreno A, Noack ES, Turner E, Villaluenga A, Gaudzinski-Windheuser S (2018) The origins of bone tool technologies: An introduction In: Hutson, J.M., García-Moreno, A., Noack, E.S., Turner, E., Villaluenga, A., Gaudzinski-Windheuser, S., (Eds.), *Römisch- Germanisches Zentralmuseum – TAGUNGEN*. Verlag des Römisch-Germanischen Zentralmuseums, Band 35, 1–4
- Jéquier CA, Romandini M, Peresani M (2012) Les retouchoirs en matières dures animales: une comparaison entre Moustérien final et Uluzzien. *C R Palevol* 11:283–292
- Kassambara A (2017) Practical Guide to principal component methods in R (Multivariate Analysis). In: *STHDA*. p. 1975721136
- Kolobova K, Kharevich V, Chistyakov P, Kolyasnikova A, Kharevich A, Baumann M, Markin S, Olsen JW, Krivoshepin A (2022) How Neanderthals gripped retouchers: experimental reconstruction of the manipulation of bone retouchers by Neanderthal stone knappers. *Archaeol Anthropol Sci* 14:26. <https://doi.org/10.1007/s12520-021-01495-x>
- Leonardi P (1979) Una serie di ritoccatoi prevalentemente musteriiani del Riparo Tagliente in Valpantena presso Verona. *Preist Alp* 15:7–15
- Malerba G, Giacobini G (2002) Fiche éclats diaphysaires avec marques transversales d'utilisation. In: Patou-Mathis, M. (Ed.), *Retouchoirs, Compresseurs, Percuteurs...Os à Impressions et à Éraillures. Fiches Typologiques de l'Industrie Osseuse Préhistorique, Cahier X*. Éditions Société Préhistorique Française, Paris, 29–37
- Mallye J-B, Thiébaud C, Mourre V, Costamagno S, Claud É, Weisbecker P (2012) The Mousterian bone retouchers of Noisetier Cave: experimentation and identification of marks. *J Archaeol Sci* 39(4):1131–1142. <https://doi.org/10.1016/j.jas.2011.12.018>
- Martellotta EF, Delpiano D, Govoni M, Nannini N, Duches R, Peresani M (2020) The use of bone retouchers in a Mousterian context of Discoid lithic technology. *Archaeol Anthropol Sci* 12:228. <https://doi.org/10.1007/s12520-020-01155-6>
- Mateo-Lomba P, Fernández-Marchena JL, Ollé A, Cáceres I (2020) Knapped bones used as tools: experimental approach on different activities. *Quat Int* 569–570:51–65. <https://doi.org/10.1016/j.quaint.2020.04.033>
- Micó C, Blasco R, Muñoz Del Pozo A, Jiménez-García A, Rosell J, Rivals F (2023) Differentiating taphonomic features from trampling and dietary microwear, an experimental approach. *Hist Biol*. <https://doi.org/10.1080/08912963.2023.2184690>
- Mozota M (2009) El utillaje óseo musteriense del nivel “D” de Axlor (Dima, Vizcaya): análisis de la cadena operativa. *Trab Prehist* 66:27–46
- Mozota M (2015) Un análisis tecno-funcional de los retocadores óseos musterienses del norte de la Península Ibérica, y su aplicación al estudio de los grupos neandertales. *Munibe Antrol Arkeol* 66:5–21
- Mozota Holgueras M (2012) El hueso como materia prima: El utillaje óseo del final del Musteriense en el sector central del norte de la Península Ibérica. PhD Dissertation. Universidad de Cantabria
- Mozota M (2013) An experimental programme for the collection and use of retouching tools made on diaphyseal bone splinters. *EXARC Journal* 2. <http://journal.exarc.net/issue-2013-2>
- Neruda P, Lázníčková-Galetová, M (2018) Retouchers from mammoth tusks in the Middle Palaeolithic: A case study from Kůlna Cave layer 7a1 (Czech Republic). In: Hutson, J.M., García Moreno, A., Noack, E.S., Turner, E., Villaluenga, A., Gaudzinski-Windheuser, S. (Eds.), *The Origins of Bone Tool Technologies*. Römisch-Germanisches Zentralmuseum – TAGUNGEN. Verlag des Römisch-Germanischen Zentralmuseums, Band 35, 215–234
- Outram AK (2008) Introduction to experimental archaeology. *World Archaeol* 40:1–6. <https://doi.org/10.1080/00438240801889456>
- Patou-Mathis P, Schwab C (2002) Fiche générale. In: Patou-Mathis, M. (Ed.), 2002. *Retouchoirs, compresseurs, percuteurs. Os à impressions et éraillures*, Société Préhistorique Française, Fiches de la Commission de nomenclature sur l'industrie de l'os préhistorique, Cahier vol. X, 11–19
- Perdegnana A, García-Antón MD, Ollé A (2017) Structural study of two quartzite varieties from the Utrillas facies formation (Olmos de Atapuerca, Burgos, Spain): From a petrographic characterisation to a functional analysis design. *Quat Int* 433(Part A):163–178. <https://doi.org/10.1016/j.quaint.2015.06.031>
- Pérez L, Hernández CM, Galván M (2019) Bone retouchers from the Middle Palaeolithic site of El Salt, Stratigraphic Unit Xa (Alicante, Spain): First data and comparison with the Middle to Upper Pleistocene European record. *Int J Osteoarchaeol* 29(2):238–252. <https://doi.org/10.1002/oa.2732>
- Picazo MJV, Morgado-Rodríguez A, Fanlo LJ, Pérez-Lambán F (2020) El aprovechamiento histórico del sílex para piedras de fusil. El caso del río Huerva (Zaragoza). *Zephyrus*, 86, 191–216. <https://doi.org/10.14201/zephyrus202086191216>
- Rendu W, Renou S, Kolyasnikova A, Baumann M, Plisson H, Discamps E, Soulier M-C, Gicqueau A, Augoyard M, Bocquel M, Guerin G, Shnaider S, Kolobova K (2023) Neanderthal subsistence at Chez-Pinaud Jonzac (Charente-Maritime, France): A kill site dominated by reindeer remains, but with a horse-laden diet? *Front Ecol Evol* 10:1085699. <https://doi.org/10.3389/fevo.2022.1085699>
- Rigaud A (1977) Analyse typologique et technologique des grattoirs magdaléniens de La Garenne à Saint-Marcel (Indre). *Gallia Préhistoire* 20:1–43
- Roberts M, Parfitt S (1999) Boxgrove: A Middle Pleistocene hominid site at Earham Quarry, Boxgrove, West Sussex. London: English Heritage Monograph 17. ISBN: 9781848021983
- Rosell J, Blasco R, Campeny G, Díez JC, Alcalde RA, Menéndez L, Arsuaga JL, Bermúdez de Castro JM, Carbonell E (2011) Bone as a technological raw material at the Gran Dolina site (Sierra de Atapuerca, Burgos, Spain). *J Hum Evol* 61(1):125–131. <https://doi.org/10.1016/j.jhevol.2011.02.001>
- Rosell J, Blasco R, Martín-Lerna I, Barkai R, Gopher A (2018) When discarded bones became important: new bone retouchers from the Lower sequence of Qesem Cave, Israel (ca. 300–420 ka). In: Hutson, J.M., García Moreno, A., Noack, E.S., Turner, E., Villaluenga, A., Gaudzinski-Windheuser, S. (Eds.), *The Origins of Bone Tool Technologies*. Römisch-Germanisches Zentralmuseum – TAGUNGEN. Verlag des Römisch-Germanischen Zentralmuseums, Band 35, 165–196
- Saville A (1981) Grimes Graves, Norfolk, Excavations 1971–72, Volume 2: The Flint Assemblage. London: Department of the Environment Archaeological Report 11
- Semenov SA (1956) Retouchoirs de pierre du Paléolithique récent. In: Okladinov, A.P. (Ed.), *Paléolithique et Néolithique de l' U.R.S.S*. *Annals du Centre d'Études et de Documentation Paléontologiques* 18, 382–387
- Shipman P, Rose J (1983) Early hominid hunting, butchering, and carcass-processing behaviors: Approaches to the fossil record. *J Anthropol Archaeol* 2(1):57–98. [https://doi.org/10.1016/0278-4165\(83\)90008-9](https://doi.org/10.1016/0278-4165(83)90008-9)
- Shipman P (1981) Life History of a Fossil. An Introduction to Taphonomy and Paleoecology. Harvard, Boston

- Siret ML (1925) L'emploi de l'os dans la retouche des silex moustériens. *Bull Soc Prehist Fr* 22:208–210
- Smith GM (2013) Taphonomic resolution and hominin subsistence behaviour in the Lower Palaeolithic: differing data scales and interpretive frameworks at Boxgrove and Swanscombe (UK). *J Archaeol Sci* 40(10):3754–3767. <https://doi.org/10.1016/j.jas.2013.05.002>
- Snyder WD, Boysen D, Orellana Figueroa JD, Tennie C, Reeves JS (2023) An overview of standardizable raw materials for controlled knapping experiments. *OSF Preprints*. <https://doi.org/10.31219/osf.io/edkge>
- Stout D, Apel J, Commander J, Roberts M (2014) Late Acheulean technology and cognition at Boxgrove, UK. *J Archaeol Sci* 41:576–590. <https://doi.org/10.1016/j.jas.2013.10.001>
- Tartar É (2012) Réflexion autour de la fonction des retouchoirs en os de l'Aurignacien ancien. *Bull Soc Préhist* 109:69–83
- Tolar J, Teitelbaum SL, Orchard PJ (2004) Osteopetrosis *NEJM* 351(27):2839–2849
- Toniato G, Münzel S, Starkovich B, Conard N (2018) Middle and upper palaeolithic bone retouchers from the Swabian Jura. *Raw Materials, Curation and Use*
- Turner E, Humphrey L, Bouzouggar A, Barton N (2020) Bone retouchers and technological continuity in the Middle Stone Age of North Africa. *PLoS ONE* 15(3):e0230642. <https://doi.org/10.1371/journal.pone.0230642>
- Valensi P (2002) Fiche extrémités distales d'humérus de grands ongulés. In: Patou-Mathis, M. (Ed.), *Retouchoirs, Compresseurs, Percuteurs...Os à Impressions et à Éraillures. Fiches Typologiques de l'Industrie Osseuse Préhistorique, Cahier X. Éditions Société Préhistorique Française, Paris*. 75–85
- Verna C, d'Errico F (2011) The earliest evidence for the use of human bone as a tool. *J Hum Evol* 60(2):145–157. <https://doi.org/10.1016/j.jhevol.2010.07.027>
- Veselsky AP (2008) Kabazi V: Bone and stone tools used in flint knapping. Kabazi V: Interstratification of Micoquian & Levallois- Mousterian camp sites 427–453
- Villa P, Mahieu E (1991) Breakage patterns of human long bones. *J Hum Evol* 21(1):27–48. [https://doi.org/10.1016/0047-2484\(91\)90034-S](https://doi.org/10.1016/0047-2484(91)90034-S)
- Vincent A (1993) L'outillage osseux au Paléolithique moyen: Une nouvelle approche. Ph.D. Dissertation, Université de Paris X
- Yardley BWD, MacKenzie WS, Guilford C (1990) *Atlas of Metamorphic Rocks and Their Textures*. Longman Scientific & Technical, New York
- Yellen JE (1977) *Archaeological Approaches to the Present: Models for Reconstructing the Past*. Academic Press, New York
- Zhang S, Doyon L, Zhang Y, Gao X, Chen F, Guan Y, d'Errico F (2018) Innovation in bone technology and artefact types in the late Upper Palaeolithic of China: Insights from Shuidonggou locality 12. *J Archaeol Sci* 93:82–93. <https://doi.org/10.1016/j.jas.2018.03.003>
- Zhu K, Prince RL (2015) Lifestyle and Osteoporosis. *Curr Osteoporos Rep* 13:52–59. <https://doi.org/10.1007/s11914-014-0248-6>

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