Journal of Archaeological Science 151 (2023) 105739

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: www.elsevier.com/locate/jas

Unraveling Neolithic sharp-blunt cranial trauma: Experimental approach through synthetic analogues

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A R T I C L E I N F O

Keywords:
Synbone sphere
Stone axe
Stone adze
Weapon-tool
Fracture pattern
Skull

A B S T R A C T

Interpersonal violence in the past is studied from different perspectives, one of which is experimentation. Using analogues to the human skeleton it is possible to replicate fractures found in the archaeological record and understand how they were produced. The main objective of this paper is to describe and differentiate sharp-blunt force cranial trauma caused by stone axes and adzes, to test previous interpretations of an archaeological case. This will create a comparative frame of reference for future studies. In the present experiment, seven Synbone polyurethane spheres were used as analogues to the human skull. These were covered with rubber skin, filled with ballistic gelatin, and fixed in a way that allowed some mobility when struck. This system creates a skin-skull-brain-neck model. A replica of a stone axe and adze were used as weapon-tools, simulating a face-to-face attack. The results of the experiment showed that there are a series of characteristics that differentiate the fracture pattern associated with each one, confirming previous bioarchaeological interpretations. The differentiation between both weapon-tools through the resulting cranial trauma allows conclusions about the direction of the blow and the position of the attacker with respect to the victim. This provides a better reconstruction of the most likely scenario surrounding the confrontation and the possible cause of death of the individuals, which is especially important during the Neolithic period, when this type of cranial trauma is very common.

1. Introduction

Penetrating perimortem cranial trauma patterns constitute important evidence of episodes of interpersonal violence in prehistory that, on many occasions, proved fatal. These injuries have been frequently documented in the archaeological record of Neolithic and Bronze Age Europe (Wild et al., 2004; Schulting and Wysocki, 2005; Meyer et al., 2009, 2015, 2018; Jiménez-Brobeil et al., 2009; Nájera et al., 2010; Schulting and Fibiger, 2012; Fibiger et al., 2013, 2023; Chenal et al., 2015; Konopka et al., 2016; Dyer and Fibiger, 2017; Madden et al., 2018; Sánchez-Barba et al., 2019; Alt et al., 2020; Janković et al., 2021). The head is one of the main targets in violent interpersonal confrontations at close range, especially when the intention is to cause the greatest possible harm to the opponent (Lovell, 1997; Brink et al., 1998; Kimmerle and Baraybar, 2008; Smith, 2017), often proving fatal. When studying cranial fractures, it is essential to differentiate between intentional and accidental injuries, since the interpretation of the potential cause of death of individuals depends on it. One of the most frequently used forensic criteria is the Hat-Brim-Line rule (HBL) (Kremer et al., 2008; Kremer and Sauvageau, 2009; Guyomarc'h et al., 2010; Kranioti, 2015). This approach estimates whether a fracture was more likely caused by interpersonal violence or by accident according to its location on the skull, its size, and the presence of other injuries. Morphological features of the fracture also play a fundamental role in the interpretation of its etiology. Certain objects used as weapons in violent confrontations can leave, in a more or less evident way, the imprint of their shape on the cranial vault (Martin and Frayer, 1997; Schulting and Wysocki, 2005; Kimmerle and Baraybar, 2008; Wedel and Galloway, 2014; Downing and Fibiger, 2017; Gummesson et al., 2018; Tornberg and Jacobsson, 2018; Dyer, 2019; Moreno-Ibáñez et al., 2021). In such cases, the

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https://doi.org/10.1016/j.jas.2023.105739
Received 7 December 2022; Received in revised form 26 January 2023; Accepted 31 January 2023
Available online 3 February 2023
0305-4403/

possibility of accidental trauma would be ruled out.

It is not always possible to determine the object used as weapon from the resulting cranial trauma, because the shape of the fracture is without a clear morphology or too ambiguous to be associated with a specific object (Schulting and Fibiger, 2012; Fibiger et al., 2013; Martin and Harrod, 2015; Janković et al., 2021). However, when weapon identification has been possible, among the blunt objects suggested to have been used as weapons during the Neolithic we find: stone maces (Schulting and Wysocki, 2005; Madden et al., 2018), wooden clubs (Schulting and Wysocki, 2005; Teschler-Nicola, 2012; Smith, 2014; Dyer and Fibiger, 2017), antler picks or spears (Schulting and Wysocki, 2005; Ahlström and Molnar, 2012; Gummesson et al., 2018), stone axes (Meyer et al., 2009; Konopka et al., 2016) and stone adzes (Wahl and Trautmann, 2012; Meyer et al., 2015; Moreno-Ibáñez et al., 2021). Several previous experimental studies have aimed to define and identify the characteristics of fracture patterns caused by blunt objects, such as maces or clubs (Gurdjian et al., 1950; Thali et al., 2002a; Kroman et al., 2011; Dyer and Fibiger, 2017; Dyer, 2019; Ruchonnet et al., 2019). These objects can generate a wide variety of fracture patterns, among which depressed, stellate or linear fractures predominate (Lovell, 1997; Kimmerle and Baraybar, 2008; Symes et al., 2012; Wedel and Galloway, 2014; Kranioti, 2015; Dyer, 2019). Depressed fractures are frequently characterized by circular or oval outlines. Linear fractures occur when the area of the object, or surface impacting the cranium does not involve a projecting element that depresses a delimited area of bone, with energy dissipating over a large area instead. The latter can occur during impacts with flat surfaces such as falls, as well as blows from larger objects, whilst stellate fractures comprise multiple linear fractures which radiate outwards from a single point of impact. Objects which combine sharp and blunt force characteristics, such as axes and adzes, are common in the archaeological record of the European Neolithic and Chalcolithic (Doperè and Vermeersch, 1978; Gibaja et al., 2012; Rojo Guerra et al., 2012; Masclans Latorre et al., 2017; Barandiarán et al., 2019). Experiments with these have been carried out on long bones (Okaluk and Greenfield, 2022), and there are also studies involving bronze axes (Downing and Fibiger, 2017), but no experimental studies on cranial trauma caused by stone axes and adzes have been published to date.

The experimental approach is widely used in both, forensic sciences and archaeology. There are three types of analogues to the living human body that can be used in these studies: human corpses, animal bodies and bones, or synthetic materials. Human corpses or embalmed cadavers have been used on numerous occasions for experiments on violence and bone fracturing during the 20th century (Gurdjian et al., 1950; Huelke, 1961; Hodgson, 1967; Yoganandan et al., 1995; Yoganandan and Pintar, 2004). More recently, the use of such analogues is rarer, due to ethical considerations and because of the limited availability of sample remains. However, experiments of forensic interest continue to be carried out using human bodies in the so-called “Body Farms” (Bell et al., 1996; Bass, 1997; Bass and Jefferson, 2004; Christensen et al., 2014; Vidoli et al., 2017). Animal analogues continue to be used for bone fracture experiments, for both, archaeological (Smith et al., 2007; Lewis, 2008; O’Driscoll and Thompson, 2014; Brinker et al., 2016; Duches et al., 2016) and forensic studies (Liebschner, 2004; Calce and Rogers, 2007; Lynn and Fairgrieve, 2009; Jordana et al., 2013b; Taylor et al., 2020). The limitation of animal analogues is that neither the biomechanical properties of bone of most species, nor their soft tissue covering is immediately comparable to the human body and skeleton (Liebschner, 2004; Dyer, 2019). Moreover, in the specific case of the human cranial vault, its shape restricts the use of animal skulls as analogues.

In recent years synthetic materials have become commonly used models in experimental trauma studies. Synbone spheres are specifically designed to replicate the biomechanical response of the human cranial vault, at least at the macroscopic level (Smith et al., 2015; Dyer, 2019). They are widely used in forensic investigations, especially in ballistic experiments (Thali et al., 2002b; Smith et al., 2015; Mahoney et al., 2018; Taylor et al., 2022), allowing the identification of bullet entry and exit holes, the direction of the shot, and even the position of and distance between the attacker and the victim. Experiments of forensic interest have also been carried out with blunt force using Synbone spheres, both in controlled laboratory contexts (Thali et al., 2002a), and in actualistic studies in which the researchers themselves handle the weapons (Ruchonnet et al., 2019). The advantage of this methodology is that it is not only applicable to forensic cases, but can also be adapted to archaeological studies, for example on prehistoric weapons (Downing and Fibiger, 2017; Dyer and Fibiger, 2017; Dyer, 2019; Strong and Fibiger, 2023). Results help to identify interpersonal violence in the past and to draw conclusions about similar weapons in the present.

Neolithic axes and adzes are objects that would have seen daily use as tools for different tasks, such as agriculture or woodworking, and also fulfill a dual role, at times being used as weapons when required. They are therefore termed weapon-tools (Golitko and Keeley, 2007; Harding, 2007; Meyer et al., 2009, 2015; Schulting and Fibiger, 2012; Konopka et al., 2016; Moreno-Ibáñez et al., 2021; Fibiger et al., 2023). No experimental studies have been carried out with these weapon-tools to date because their combination of blunt force trauma and sharp force trauma characteristics (Alunni-Perret et al., 2005; König and Wahl, 2006; Kimmerle and Baraybar, 2008) allows them to be differentiated from blunt objects such as maces or clubs most of the time. On some occasions, the use of stone axes and/or adzes, or axe-like objects, has been inferred, but without distinguishing between one or the other (Golitko and Keeley, 2007; Teschler-Nicola, 2012; Smith, 2017). Although the cutting edge of both objects is very similar, axes are hafted with the cutting edge parallel to the handle, while adzes are hafted with their cutting edges perpendicular to the handle. For this reason, our starting hypothesis is that the dispersion of force and, therefore, fracture propagation differs from one to the other, and by differentiating them it is possible to estimate the direction of the blow. This would allow, in the case of a lethal trauma, a better reconstruction of the attacker-victim constellation and context of the attack. A direct face-to-face confrontation between individuals has different implications than a blow from behind. In the first case, it is more likely to reflect an active fight (Teschler-Nicola, 2012; Sánchez-Barba et al., 2019), where in the second may be the result of a surprise attack in an ambush or an execution (Wahl and Trautmann, 2012; Meyer et al., 2015, 2018), bearing in mind that during the study of an isolated cranial trauma it is not possible to make strong statements about how the injuries occurred (Wedel and Galloway, 2014; Pinheiro et al., 2015; Spatola, 2015). Instead, interpretations are suggested based on the available evidence. The present experiment is complementary to a previous archaeological case study in which the weapon used to cause a cranial trauma and the direction of the blow were inferred through the morphological features of the injury (Moreno-Ibáñez et al., 2021). We aimed to create a frame of reference when studying this type of trauma in the archaeological record. The description and analysis of similarities and differences between the fracture patterns caused by a symmetrical vertically hafted edge (axe), versus a beveled horizontally hafted edge (adze), may be helpful for future studies on the etiology of cranial injuries.

2. Material and methods

The weapon-tools tested in the present experiment were stone axe and stone adze replicas, with a cutting-edge length of 37 mm respectively. They were made by Miquel Guardiola, archaeotechnician of the outreach department, at the Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA). Both replicas were made of serpentinite, with a maple (*Acer monpesulanum*) handle for the axe, and an oak handle (*Querqus ilex ilex*) for the adze, fastened with strips of leather. Serpentinite is a magnesium and silicate rich metamorphic rock, of variable but homogeneous grain, which fractures similar to flint and was commonly used to manufacture stone tools and ornaments throughout Europe during Prehistory. The size of the weapon-tools was chosen

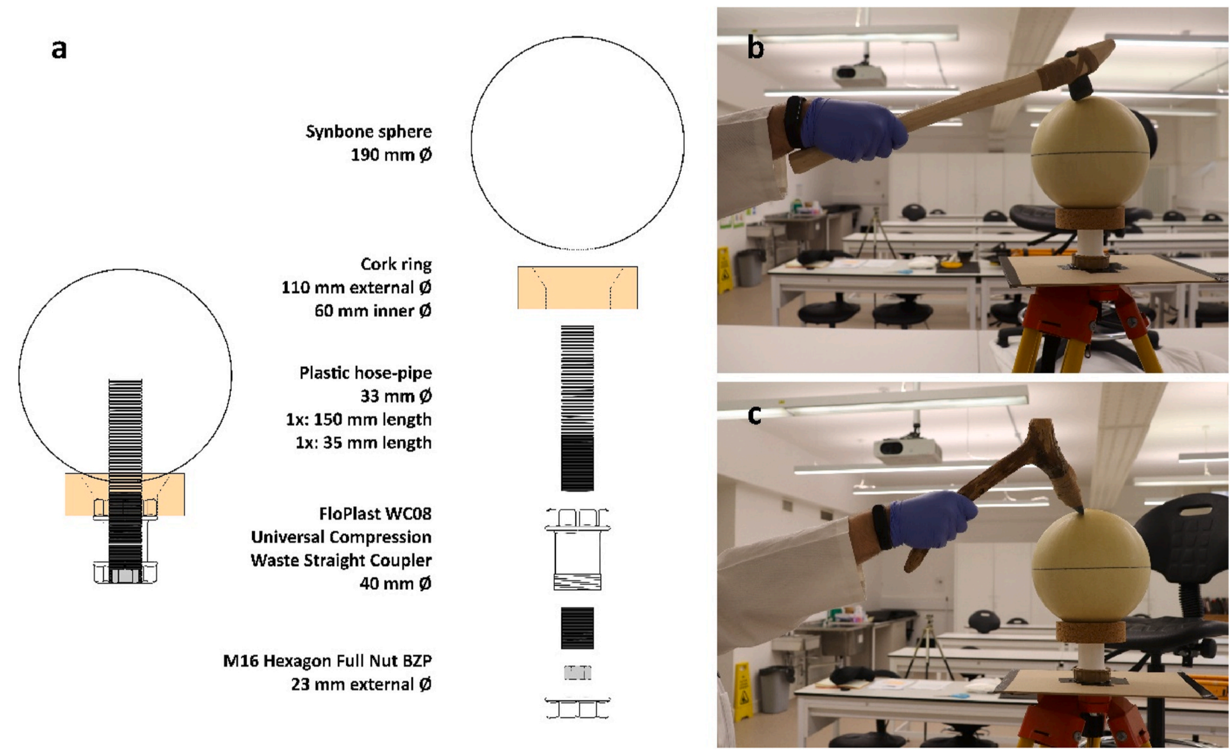

Fig. 1. Mounting System parts and positioning (a), diagram edited and extended from Dyer (2019) (160–163), and area of impact with the axe (b) and adze (c).

based on a cranial trauma documented at the Late Neolithic – Chalcolithic Cova Foradada site (Calafell, Tarragona, Spain), suggested to be the result of sharp-blunt trauma probably caused by a stone adze (Moreno-Ibáñez et al., 2021). To conduct the experiment, we used synthetic bone spheres as an analog for the human skull. The protocol followed was designed for previous experimental studies in which skin-skull-brain models were also used (Thali et al., 2002b; Carr et al., 2015; Kranioti, 2015; Smith et al., 2015; Dyer and Fibiger, 2017; Falland-Cheung et al., 2018; Mahoney et al., 2018; Dyer, 2019; Ruchonnet et al., 2019; Koppenhaver-Astrom, 2021; Taylor et al., 2022). The choice of synthetic analogues for the human cranium avoids ethical conflicts of using real human remains, and more reliably reproduces the biomechanical structure of the human skull than using animal resources.

Seven synthetic bone spheres produced by Synbone AG (2013) (Switzerland) were used, with a thickness of 7 mm, to carry out the strikes with the selected weapon-tools replicas (three strikes with an axe and four with an adze). As two of the impacts produced with the adze did not completely penetrate the sphere it was decided to use one more sphere with this object to have a more representative sample of the possible fracture pattern. The thickness of 7 mm falls within the average of anatomical variability (Lynnerup et al., 2005; Calisan et al., 2021; Rowbotham et al., 2022), and it has been shown to reliably replicate the biomechanical response of cranial bone at the macroscopic level in previous studies (Dyer and Fibiger, 2017; Dyer, 2019; Ruchonnet et al., 2019; Taylor et al., 2022). The skin-skull brain model consists of two hemispheres glued together to form a single sphere. They have an opening at the bottom (where the foramen magnum would be located) that facilitates the introduction of ballistic gelatin. In this study the spheres were filled with a solution of 10% ordnance ballistic gelatin, simulating the internal soft tissue of the cranium (Thali et al., 2002b; Carr et al., 2015; Kranioti, 2015; Smith et al., 2015; Dyer and Fibiger, 2017; Falland-Cheung et al., 2018; Mahoney et al., 2018; Ruchonnet et al., 2019; Taylor et al., 2022) and following the University of Edinburgh's protocol (Supplementary Material, SM Fig. S1). The spheres also had a rubber skin covering, which simulates the periosteum.

The mounting system for placing the spheres was prepared following the model used by Dyer and Fibiger (2017) and Dyer (2019). The aim was for the sphere to simulate as closely as possible the head of a standing person, i.e. with a neck displaying some range of motion (Fig. 1a, SM Fig. S2), therefore making the experiment more realistic. A piece of flexible hosepipe was used for this purpose, with a cork ring acting as a base (for a complete description of the protocol, see Dyer, 2019: 160–163). Once the gelatin was prepared, the experiments had to be carried out within five days for the gelatin to maintain its properties.

The experiments were conducted in two rounds, one for each weapon-tool replica used (Fig. 1b and 1c). The strikes were made by the same right-handed adult male (in this case, the corresponding author M. A. Moreno-Ibáñez, 27 years old, 176 cm tall, and weighing 87 kg). The spheres with the mounting system were placed on a survey tripod, and they were labeled to indicate the anterior, posterior, right lateral, and left lateral zones (Fig. 3, Fig. 4), using anatomical terminology as if they were real crania, thus making the analysis and description of the fractures unambiguous. To better observe the differences between the weapon-tools, in all cases the spheres were placed at a lower height than the attacker, between 1.65 and 1.50 m. One strike was delivered for each sphere, directed at the top, slightly to the left (the left parietal area in a human cranium), with the cutting edge impacting at an angle of between 45 and 90° (Supplementary Material, Video 1). The objective was not to impact the object's edge at too acute or obtuse angle, to see the effect of the entire edge and not just one corner on the sphere. After each experiment, measurements and observations were recorded, and photographs of any fractures produced were taken. This first round of data collection was completed while the spheres were still in the mounting system. When the experiments were completed, the rubber skin covering the spheres was removed, and a second set of photographs of any fractures were taken. The ballistic gelatin was then removed from each sphere, using a warm water bath.

The exact angle and force of the strikes were not measured but the entire experiment was filmed on video, so that the approximate angle of the impacts could be observed afterwards. The aim was to replicate an interpersonal attack, thus considering the natural variations that occur during confrontations in terms of force used and exact angle of impact.

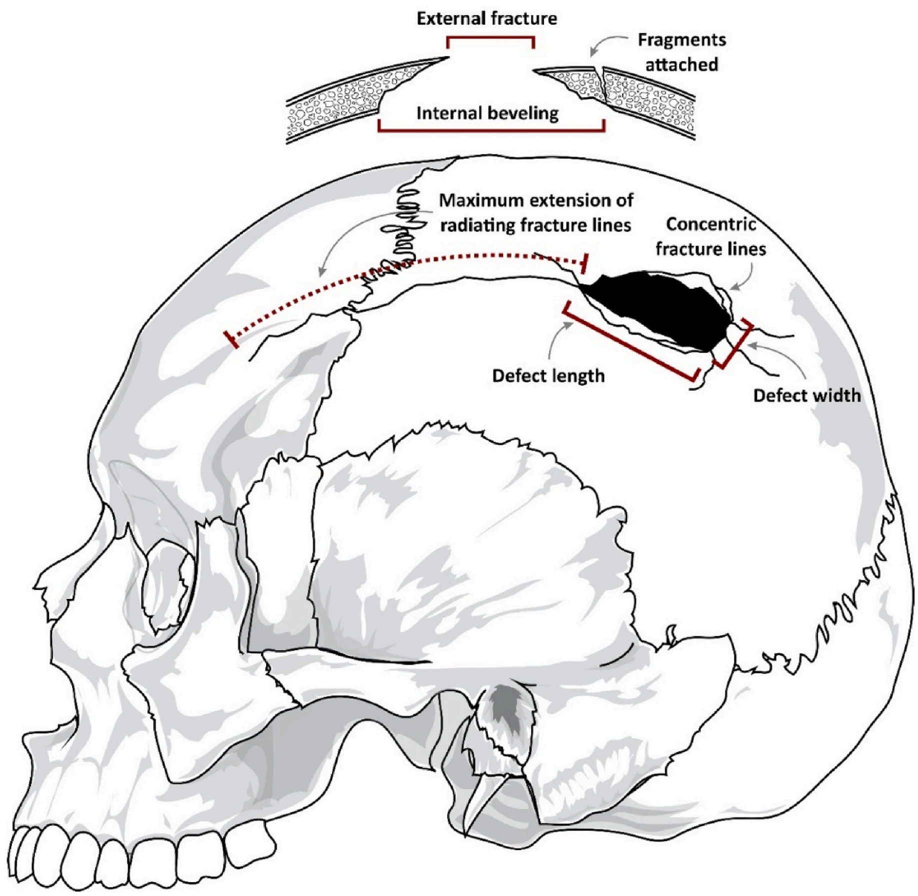

Fig. 2. Elements of a complete cranial trauma considered in the analysis of the fracture pattern (listed in Table 1).

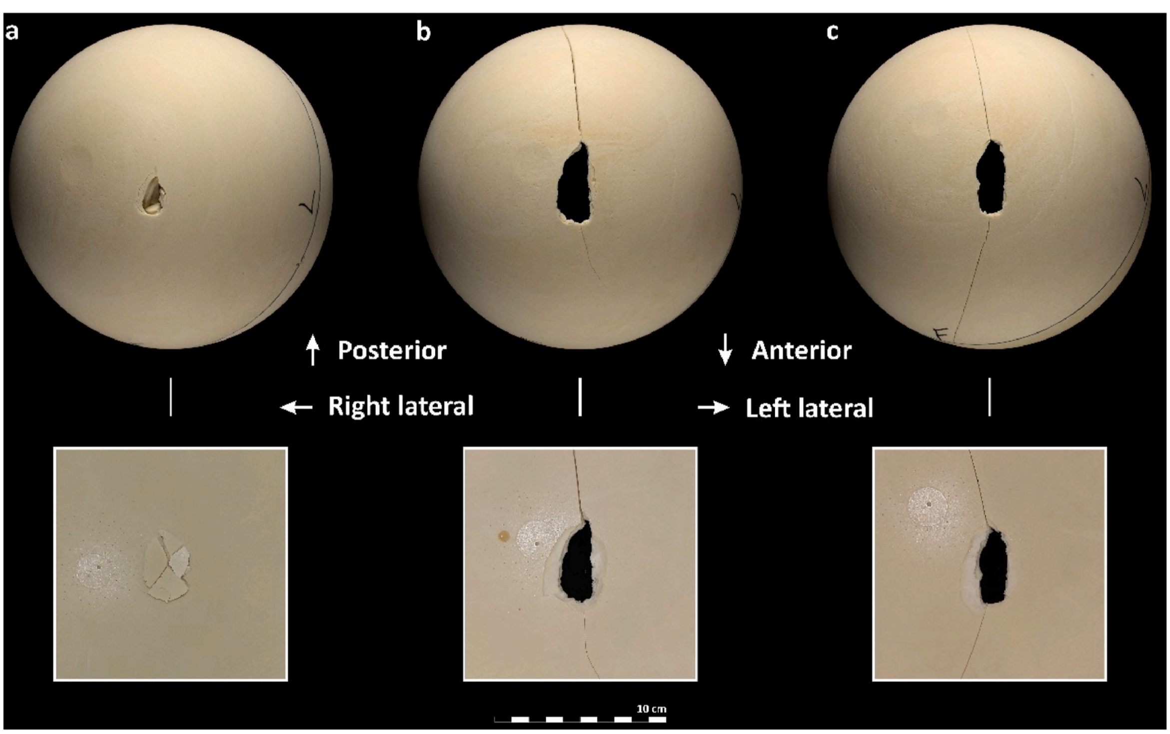

Fig. 3. Fractures resulting from blows with the stone axe, exterior and interior view.

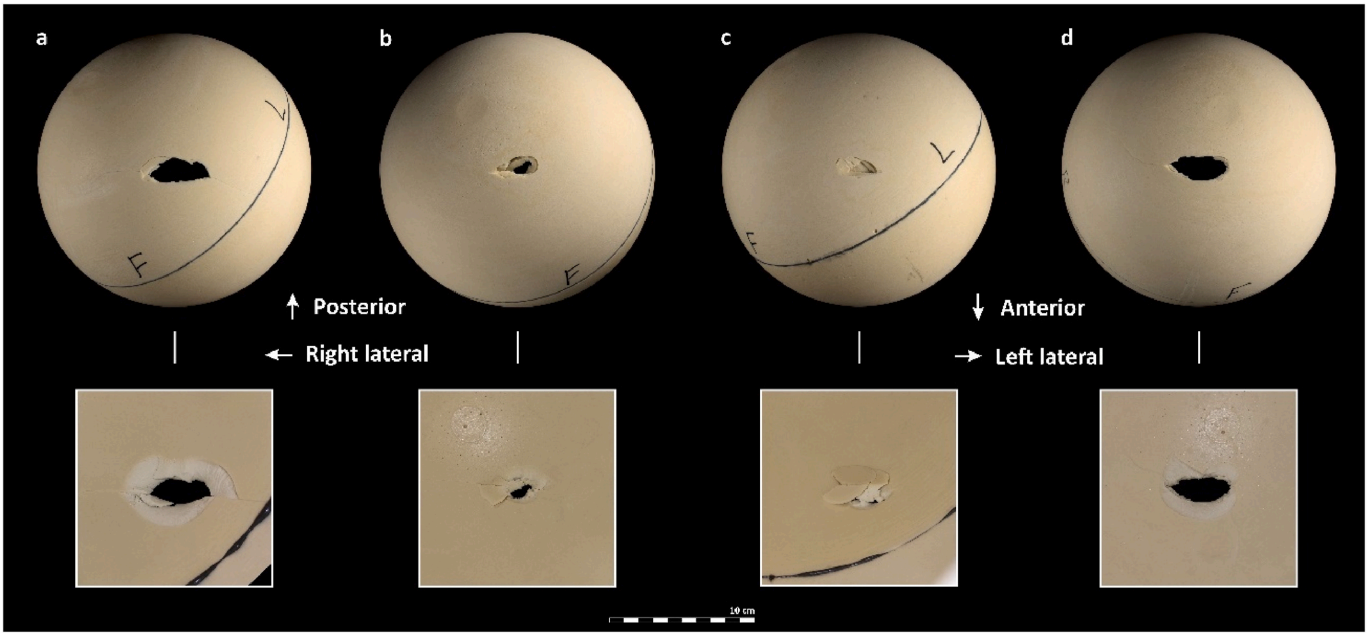

Fig. 4. Fractures resulting from blows with the stone adze, exterior and interior view.

Table 1
Information and morphological characteristics of experimental fractures.

Weapon-tool	Height (m)	Angle of impact	Length (mm)	Width (mm)	Radiating fracture line	Concentric fracture line	Maximum crack extension (mm)	Internal beveling	Fragments attached	Fragments detached
Axe 1	1.65	~45°	19.2	9.8	0	Yes	0	Yes	Yes	No
Axe 2	1.55	~45°	41.2	15.6	2	Yes	215	Yes	Yes	Yes
Axe 3	1.50	~90°	38.3	14.2	2	No	250	Yes	No	Yes
Adze 1	1.60	~90°	41	14	1	Yes	70	Yes	Yes	Yes
Adze 2	1.55	~90°	25.1	11.7	1	Yes	55	Yes	Yes	Yes
Adze 3	1.50	~90°	24.6	11.1	0	Yes	0	Yes	Yes	No
Adze 4	1.50	+90°	36	14.1	1	Yes	54	Yes	Yes	Yes

Measurements recorded with digital calipers for each fracture included length and width of the injuries, presence/absence of radial and concentric fracture lines, presence/absence and extent of endocranial damage (internal beveling), presence/absence of displaced but still attached Synbone fragments, and location of all these in relation to the point of impact (Fig. 2). We differentiated between fracture lines, as cracks on the bone, without wide opening, and fractures or defects, as complete breakage of bone, sometimes even with a missing bone fragment. All features were identified based on standard forensic criteria (Lovell, 1997; Jordana et al., 2013a; Symes et al., 2014; Wedel and Galloway, 2014; Sala et al., 2016).

3. Results

The blows delivered with the axe and adze caused a series of fractures of varying extent, from small depressions that affected mostly the outer surface of the sphere, without penetrating completely, to fractures in which the weapon-tool penetrated completely, leaving its cross-section well marked on the sphere. This variability responds to different degrees of force used during the blows, as well as to the angle of impact. In addition, if the weapon-tool is not firmly fastened to the handle, the force of the impact on the sphere may be diminished, which was the case with the second and third blow of the adze. In all cases, the rubber skin covering the spheres held the fragments in the central fracture zone in place until the silicone layer was removed. It was possible to recover all the small polyurethane fragments (SM Fig. S3), especially abundant in the most intense fractures. The measurements and characteristics of the fractures are listed in Table 1..

Axe 1 (Fig. 3a): Depressed fracture with all the fragments still attached. It has a wider and rounded outline in the anterior zone (closer to the attacker), and a more pointed outline at the posterior end. The axe struck with one of the corners, at an angle close to 45°. In this case the sphere was placed higher (1.65 m). At the posterior, pointed end of the fracture, it is possible to see a linear cut mark caused by the cutting edge of the axe. There are no radial fracture lines, but several concentric fracture lines are visible on both sides of the fracture, associated with the inward collapse of fragments of the sphere that have not been detached.

Axe 2 (Fig. 3b): Complete penetrating fracture of elongated subtriangular outline. It presents with a wider anterior part, with a quadrangular outline, where the axe penetrated deeper, and a more pointed posterior aspect. One side of the fracture is straight (left) and the other is curved (right). Two fracture lines emerge from the anterior and posterior ends of the fracture respectively. The one extending to the posterior part of the sphere shows a considerable opening, reaching the lower hemisphere (215 mm long). The anterior fracture line is smaller and shorter, 63 mm long, and slightly curved. On the straight side of the fracture (lateral left) there is a concentric linear fracture, related to a fracture fragment that has been depressed inwards and has not been detached. Internal beveling is observed, with a similar extension to the right and left sides of the fracture.

Axe 3 (Fig. 3c): Complete penetrating fracture of elongated, symmetrical, and almost oval morphology. The anterior part has a quadrangular outline, and the posterior is more curved and slightly pointed. Two very marked and wide radiating fracture lines extend from both ends. The posterior one reaches the line of separation of the hemispheres (160 mm), while the anterior one extends to the opening at

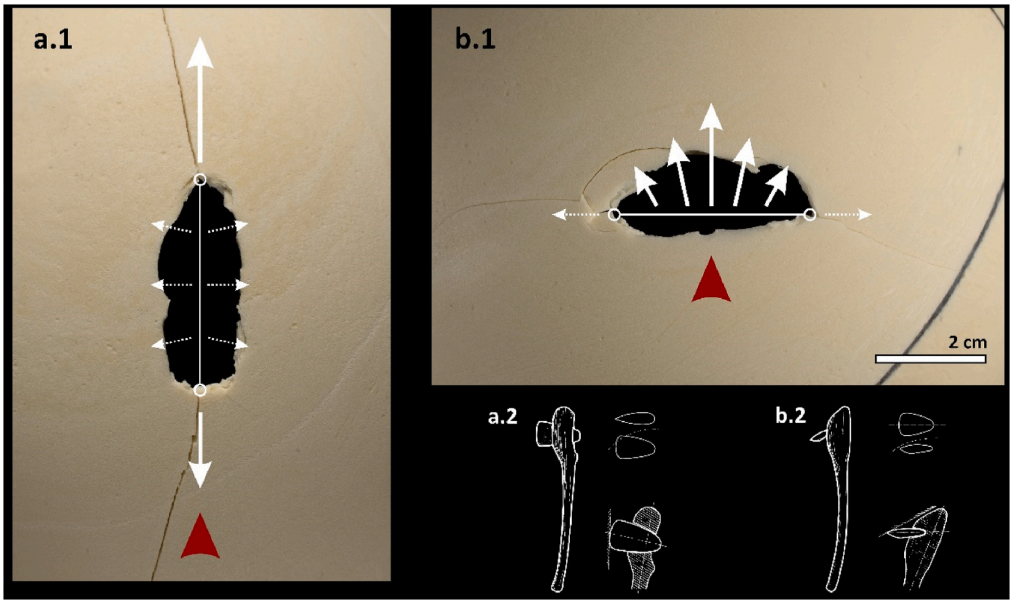

Fig. 5. Fracturing and force dispersion pattern of the Synbone sphere using a stone axe (a.1 and a.2) and an adze (b.1 and b.2). The fracture caused by the axe corresponds to Axe strike 3 and the adze fracture to Adze strike 1. Both cases best represent the fracture pattern characteristics of each weapon-tool. The straight line with circles at each end represents the point of impact. The red arrow indicates the direction of the blow. The larger white arrows represent the greater dispersion of force, and the smaller dotted white arrows represent a smaller dispersion of force. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the base of the sphere (250 mm long). There are no concentric fracture lines. The inner surface shows greater beveling on the right side of the fracture, with a convex shape.

Adze 1 (Fig. 4a): Complete penetrating fracture of elongated morphology with pointed ends. One fracture side is straight (anterior), corresponding to the impact point, and the other is convex (posterior). There are two narrow radial fracture lines extending from both ends (50 and 70 mm in maximum length), curving in an anterior direction. The fracture has concentric fracture lines, more marked on the posterior aspect, related to fragments of the sphere that have not been detached. The area of the sphere opposite to the point of impact (curved side of the fracture) is slightly depressed. The internal beveling is broader on the posterior side of the fracture.

Adze 2 (Fig. 4b): Complete depressed fracture with an oval outline. One end is rounded (lateral left) and the other is pointed (right). A small cut caused by the edge of the adze can be seen at the pointed end. A linear fracture is located towards the right lateral aspect of the sphere (55 mm long), which is close but not joined to the fracture perimeter. There is a concentric fracture line on the left side of the fracture, which does not join with the fracture. Most of the fragments of the sphere remained attached to the circumference of the fracture, visible from both the outside and inside of the sphere.

Adze 3 (Fig. 4c): Incomplete depressed fracture of semicircular outline. It has a straight side (anterior) and a curved and convex side (posterior) with multiple concentric fracture lines, corresponding to small fragments that have not been detached. The internal surface features fractured but still attached fragments.

Adze 4 (Fig. 4d): Complete penetrating fracture of semicircular outline. It has a straight side (posterior) and a curved and concave side (anterior). The lateral left end has a rounded morphology, while the right end is pointed. From that pointed end, a curved and slightly opened radial fracture line is extending up to 54 mm.

4. Discussion

Identifying a cranial fracture as intentional rather than an accidental blow, for example caused by a fall, is not always possible due to the equifinality of injuries of different etiology. The two factors that play a fundamental role in this differentiation are the location of the trauma on the cranium and its morphological characteristics (Brink et al., 1998; Kremer et al., 2008; Brink, 2009; Jordana et al., 2013a; Wedel and Galloway, 2014; Kranioti, 2015). Being able to link cranial trauma to an object as specific as a stone axe or adze removes doubts about the etiology of the fracture, directly relating it to an interpersonal attack. This is especially important from the Neolithic period onwards, when these weapon-tools appeared. This period also exhibits an increase of violence in the archaeological record, related both to an intensification of sporadic crisis within the European Neolithic societies (Wild et al., 2004; Beyneix, 2007; Golitko and Keeley, 2007; Schulting and Fibiger, 2012; Fibiger et al., 2013, 2023; Meyer et al., 2015; Soriano et al., 2015; Alt et al., 2020) and to a greater preservation of skeletal remains available to study thanks to the practice of collective burials and to a more systematic general funerary treatment. In these contexts of interpersonal and intergroup violence, cranial injuries caused by stone axes and adzes are abundant (Meyer et al., 2009, 2015; Wahl and Trautmann, 2012; Konopka et al., 2016). For this reason, this experimental study of the fracture pattern associated with these weapon-tools allows for more detailed trauma-weapon characterization. The objective is to test whether the different position of the cutting edge of the objects with respect to their handle translates into distinguishably different fracture patterns on the cranial vault.

Cranial fractures caused by stone axes and adzes in the current study are unsurprisingly similar in their general characteristics: in both cases, their use resulted in depressed fractures, with and without complete penetration. In all cases, the blows also affected the internal surface of the sphere, although in some cases fracture fragments were not completely detached. In a previous study of an archaeological case (Moreno-Ibáñez et al., 2021), it was proposed that the differences between the cranial fractures caused by both objects lie in the location of the area of greatest destruction with respect to the point of impact, mainly due to the position of the object in relation to the handle (vertical or horizontal). The present experiment demonstrates that, although axes and adzes are very similar weapon-tools, there are a number of characteristics in the fracture patterns they cause that allow differentiation between the two. What this study also shows is the variability in fracture morphology, even when fractures are made by the same attacker and the same weapon-tool.

Fractures caused by an axe are characterized by a symmetrical oval or drop-shaped fracture outline, with the point of impact located approximately at the center of the fracture, and very marked and open radiating fracture lines emerging from both ends of the impact point (especially at the distal end, as related to the direction of the blow) (Fig. 5a). These features have been observed in archaeological (Meyer et al., 2009; Konopka et al., 2016), experimental (Downing and Fibiger, 2017), and forensic cases (Kimmerle and Baraybar, 2008). In the present experiment, we observed this symmetry in Axe strike 1 and Axe strike 3 fractures, reflecting the symmetrical morphology that characterizes the stone axe's edge. The first of these cases corresponds to a blow of moderate intensity with the lower corner of the axe, at an angle close to 45°, without complete penetration into the sphere. This type of fracture, with a subtriangular shape, is very common when the primary impact is with one end of the axe only (Kimmerle and Baraybar, 2008; Konopka et al., 2016). With the present experiment, we suggest that this angle of impact is related to a similarity in height between the attacker and victim. Axe strike 3 represents complete penetration of the axe into the sphere, at an angle close to 90°, resulting in a defect mirroring the cross-section of the weapon. This complete penetration of the axe into the sphere is possible because of a height difference between the attacker and the sphere, or because of a greater length of the handle of the weapon-tool.

The fracture resulting from Axe strike 2 is slightly different. It has one straight and one convex side. This is one of the criteria used in the previous study (Moreno-Ibáñez et al., 2021) for the identification and definition of cranial fractures caused by adzes, with the straight side of the fracture representing the point of impact, and the convex side, with greater bone destruction, representing the direction of the blow. In this case, a radiating fracture line, rather wide and long, is emerging from the posterior end of the fracture (following the direction of the blow), which did not occur with any of the adze strikes (and it's very similar to the radiating fracture lines of Axe strike 3). The extent of damage is linked to a greater dispersion of force in the direction in which the blow is inflicted. For this reason, the very marked radiating fracture lines emerging from the distal end of the fracture are one of the aspects that characterize fractures produced by this object (Kimmerle and Baraybar, 2008; Meyer et al., 2009; Konopka et al., 2016; Moreno-Ibáñez et al., 2021). The fracture caused by Axe strike 3 is the one that most clearly combines all the characteristics of the cranial fracture pattern caused by axes.

Fractures resulting from adze strikes, in almost all cases (Adze 1, 2, and 3), feature one straight (point of impact) and one convex side (dispersion of the force following the direction of the blow). The most representative case is Adze strike 1, which was delivered with the greatest force (Fig. 5b). This fracture shows all the characteristics described in the archaeological case study of Moreno-Ibáñez et al. (2021) on a fracture caused by a stone adze.

- The impact point is located on the straight side of the fracture outline.
- The area of greater destruction (curved/convex side) indicates the direction of the blow (perpendicular dispersion with respect to the impact point).
- Radiating fracture lines emerge from both ends of the impact point (of smaller extension and opening than the radiating fracture lines caused by the axe).
- Concentric fracture lines on the side opposite (distal) the point of impact (in this case related to fragments that have not been detached).
- Greater internal delamination on the distal side of the fracture, also associated with the direction of the blow.
- The area opposite to the point of impact is often slightly depressed due to the greater pressure applied in that zone.

Adze strikes 2 and 3 also have a straight side (more evident in Adze strike 3), associated with the point of impact, opposite to the side of greater destruction (with more depressed fragments and concentric fracture lines). In both cases, however, it is only possible to see a V-shaped end (right lateral), since the adze impacted obliquely, with only one corner. Adze strike 3 is the most superficial, in a more lateral location on the sphere. The edge of the adze impacted more obliquely, even causing the adze to come loose from the handle. In all three cases,

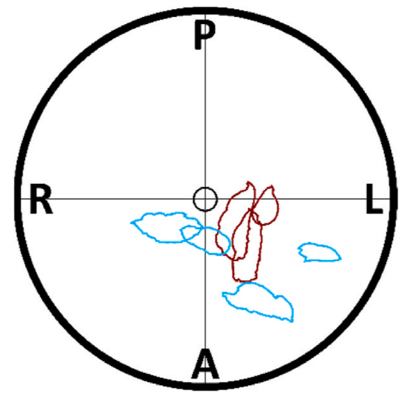

Fig. 6. Diagram of the top view of a Synbone sphere and location of axe (red) and adze (green) fractures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the adze impacted the sphere at an angle of about 90°, and all fractures have greater internal beveling on the side opposite to the point of impact, related to the direction of the blow.

Adze strike 4 has different characteristics. In this case, the blow was delivered from a great height, impacting with an inclination of more than 90°, and it is the only fracture produced on the right side of the sphere. Due to the greater inclination in the impact, the fracture has an outline dissimilar to other adze fractures. The straight side of the fracture is, in this case, in a posterior position, and the curved/convex side (and slightly depressed area) in an anterior position. With these characteristics, if we consider the criteria identified and described for cranial fractures caused by adzes, it seems that the blow was delivered from a posterior direction when, in fact, the strike was delivered from the same position (SM Fig. S3), simulating a face-to-face attack. This shows the great variability possible in the fracture patterns, in which, although general criteria are maintained, the angle of impact plays a fundamental role. It is also interesting to note that the blows made with the axe have impacted in a very similar area of the sphere, while the fractures caused by the adze have a more variable location (Fig. 6). This means that with a weapon of straight morphology (i.e., handle and cutting edge are in line with each other) such as the axe, it is easier to aim and strike the desired area than with an adze, whose L-shaped morphology makes it easier to deviate when delivering the blow.

The archaeological (and forensic) implication of differentiating the weapon used and, therefore, the direction of the blow, is relevant to make interpretations about the conditions in which a given injury was produced. In addition, these results help to reduce the problems of equifinality between injuries or modifications produced in other contexts or by different taphonomic processes. The position of the attacker relative to the victim can provide information on whether it was a direct and active confrontation, that is, whether the victims were also actively engaged in fighting, or whether it was a massacre or execution of individuals, where interpersonal violence is unidirectional. Any fight between individuals is a dynamic event, so the number of variables involved in how an injury was produced is too high to be able to produce an exact reconstruction of the event, especially in archaeological cases, but on some occasions, it is possible to make general inferences or suggestions for the most likely scenario. In the Neolithic archaeological record there are abundant examples of skeletal remains interpreted as individuals who took an active part in violent confrontations (Schulting and Wysocki, 2005; Teschler-Nicola, 2012; Vegas et al., 2012; Chenal et al., 2015; Sánchez-Barba et al., 2019), but also of mass graves in which individuals were killed in ambushes or executions (Meyer et al., 2009, 2015, 2018; Wahl and Trautmann, 2012; Konopka et al., 2016; Madden et al., 2018; Alt et al., 2020). Having a mass grave in which several individuals show the same pattern of evidence of violence can give relatively clear clues about the context surrounding those

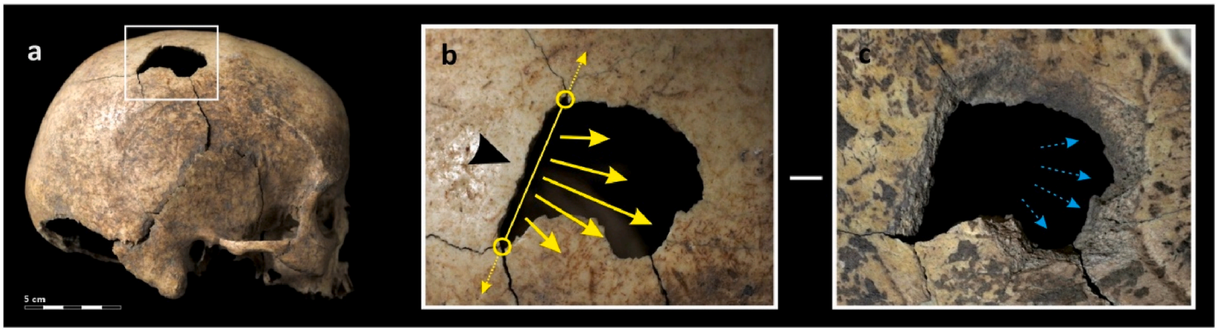

Fig. 7. Cranium E7-104 from Cova Foradada (Calafell, Spain) (a), close-up view of the fracture with the force dispersion pattern extending from the point of impact (black arrow) (b), and internal beveling more intense in the area opposite to point of impact, following the direction of the blow (c).

perimortem injuries. At the Talheim massacre (Early Neolithic, Germany) (Wahl and König, 1987; Wahl and Trautmann, 2012) it is suggested that stone adzes were the weapon used to cause the cranial trauma, and the present experimental study allows us to confirm this interpretation. It is necessary to consider, however, that not all cranial fractures from Talheim presented the morphological characters necessary to identify the weapon employed, and that other blunt objects besides adzes are likely to have been used, as it is usual in this type of prehistoric violent confrontations (Schulting and Wysocki, 2005; Fibiger et al., 2013, 2023; Martin and Harrod, 2015; Brinker et al., 2016).

When an individual with an injury is found in isolation, an even more detailed analysis of the trauma is essential to infer its etiology, always considering that different scenarios may cause similar injuries. It is always better to present the most likely cause than to make categorical statements (Pinheiro et al., 2015) since, in addition, an injury classed as perimortem is not necessarily directly linked to the death of the individual. The cranial trauma found at Cova Foradada (Calafell, Spain), is such a case of an isolated injury, where previous analysis (Moreno-Ibáñez et al., 2021), together with the present experiment, has confirmed that an attack from behind using a stone adze is the most likely explanation for the injuries observed (Fig. 7). Therefore, the characteristics of the cranial fracture, the weapon-tool used, and the direction of the blow, in addition to the absence of other individuals with lethal perimortem injuries at the site, allow the interpretation of an execution or an isolated case of fatal interpersonal violence.

5. Conclusion

Experimental data support and complement the hypothesis and descriptions in Moreno-Ibáñez et al. (2021) about the features of a cranial fracture caused by a stone adze at Cova Foradada (Calafell, Spain) during the Late-Neolithic - Chalcolithic. These cranial fractures, both described in that previous work and observed in the present experiment, are characterized by a straight side with V-shaped ends, corresponding to the point of impact, opposite to a curved side with convex outline, indicating the direction of the strike. The radiating fracture lines emerging from the ends of the point of impact are of lesser extent and aperture than those found in axe fractures. The adze fractures have a greater number of concentric fracture lines and/or depressed bone fragments opposite to the point of impact, as well as a greater extent of internal beveling in that zone. The use of synthetic models as analogues to the human cranium has once again proven to be a reliable method to test and compare the effect of different prehistoric weapon-tools. It reproduced fracture patterns that are macroscopically comparable with archaeological cases and it is a useful tool for experimental studies on bone fracturing. The differentiation between the use of different weapon-tools is a key feature in identifying the direction of the blow and, therefore, the position of the attacker with respect to the victim. This makes it possible to better reconstruct the possible scenarios in which the cranial trauma occurred, differentiating between frontal confrontation, attack from the back, lateral blows, or the height of the attacker with respect to the victim. This provides information on whether it was an active confrontation between individuals, an ambush, or an execution, in other words, whether the victim was also an attacker or not, allowing for a better understanding and implications of the cause of death.

Author contributions

M.A. Moreno-Ibáñez: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft.L. Fibiger: Conceptualization, Methodology, Supervision, Writing – review & editing.P. Saladié: Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

This work is dedicated to the memory of Miquel Guardiola, without whose contribution of the experimental weapon-tools, his comments and help in general, it would not have been possible. Thank you. I would also like to thank the School of History, Classics and Archaeology (The University of Edinburgh), for all their help and facilities provided during my stay there. Thanks to Raquel Hernando for unraveling the title, and thanks to Linda for the invention of the "Fibiger's board", which was a fundamental ally during the experiment. This work has been supported by the Spanish Ministry of Universities of Spain (FPU18-02291 grant, and EST22/00015 international short stay grant); Spanish Ministry of Science and Innovation through the "María de Maeztu" program for Units of Excellence (CEX2019-000945-M); Spanish Ministry of Economy and Competitiveness (MINECO) through Sierra de Atapuerca project (PID2021-122355NB-C32); Agència de Gestió d'Ajuts Universitaris i de Recerca (SGR 2017–1040); and Universitat Rovira i Virgili (2022PFR-URV-64).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2023.105739.

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