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When Lithics Hit Bones: Evaluating the Potential of a Multifaceted Experimental Protocol to Illuminate Middle Palaeolithic Weapon Technology

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Abstract
Recent zooarchaeological and isotope analyses have largely settled the debate surrounding Neanderthal hunting capacities, repeatedly demonstrating their successful acquisition of large ungulates. Nevertheless, the functional identification of individual tools as hunting weapons remains a methodological challenge. In-depth studies have focussed mainly on small subsets of lithic artefacts from selected assemblages assessing features of breakage patterns, retouch, shape and use wear. Studies focussing on associated hunting lesions are rarer and often focus on reconstructing very specific bone surface marks encountered in the archaeological record. This study aims to add to our understanding of the formation and characteristics of projectile impact marks (PIMs) on bone through a series of highly monitored, replicative experiments, using thrusting and throwing spears with replica Levallois points into two wild pig carcasses. In total, 152 shots were made, and for each a series of attributes was recorded, including velocity and location of impact. Subsequent quantitative analyses focussed on understanding the various factors underlying the formation of different types of projectile impact marks. These experiments demonstrate that PIM formation results from the properties of both the impacting projectile and bone element. PIMs can signal impacts caused by different delivery methods but only on some parts of the skeleton. These results are contextualised in relation to the occurrence and recognition of Palaeolithic PIMs and patterns of Neanderthal behaviour. These experiments are only a first step in improving the recognition of these signatures in the archaeological record and providing better insights into understanding of the mechanisms of Neanderthal hunting.

Keywords Neanderthal hunting · Middle Palaeolithic · Zooarchaeology · Hunting lesion · Projectile impact marks · Experimental archaeology

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Introduction

Identifying the origin and widespread use of projectile technologies, one of the most significant technological innovations in human evolution, remains a key challenge of Palaeolithic archaeology. Projectile technology permits the targeting of a broader variety of large and medium-sized terrestrial game; importantly, however, it also mitigates against risk by allowing the killing of potentially dangerous prey animals at a distance. In addition, the often complex operational and technological sequences required in the production of different projectile technologies can potentially illustrate the social and cognitive organisation of Palaeolithic groups (Shea 2006; Churchill and Rhodes 2009; Shea and Sisk 2010; Sisk and Shea 2011; Lombard and Haidle 2012; Haidle et al. 2016; Iovita and Sano 2016; but see also Schmidt et al. 2019; Smith et al. 2019).

Neanderthal populations occupied large parts of Europe and western Asia from ca. 300,000 to 40,000 years ago. Whilst debates about their capability and capacity for sophisticated behaviours are ongoing, current archaeological evidence suggests that these groups were successful hunters of various species of large to medium sized animals (Gaudzinski 1995; Marean and Kim 1998; Gaudzinski and Roebroeks 2000; Steele 2002; Villa and Lenoir 2009; Discamps et al. 2011; Morin 2012; Rendu et al. 2012; Villa and Roebroeks 2014; Morin et al. 2015; Smith 2015; Gaudzinski-Windheuser et al. 2018). Such behaviour has been identified within both glacial and interglacial phases, and though there are subtle variations in terms of the species, the overall pattern remains consistent (Gaudzinski-Windheuser et al. 2014a, b; Sinet-Mathiot et al. 2019). Furthermore, stable isotope analysis from Neanderthal fossils repeatedly illustrates values that are consistent with the consumption of large quantities of terrestrial animal protein (Bocherens et al. 2001, 2005; Richards et al. 2001; Richards and Trinkaus 2009; Britton et al. 2011; Naito et al. 2016; Jaouen et al. 2019). Despite the frequency and abundance of Middle Palaeolithic sites with butchered faunal remains, reconstructing underlying acquisition methods (Smith 2015; e.g., hunting strategy; see White et al. 2016) and technologies (e.g., wooden javelins, stone-tipped spears) often remains ambiguous (Thieme 1997; Shea 2006; Schoch et al. 2015; Gaudzinski-Windheuser 2016; Iovita and Sano 2016; Gaudzinski-Windheuser et al. 2018; Milks et al. 2019). Due to unfavourable preservation conditions, the remains of organic spears and hafts from Palaeolithic contexts are rare (Thieme 1997; Schoch et al. 2015). Therefore, recognising Neanderthal hunting technologies is mainly reliant on the identification of lithic projectile weapons from the archaeological record, alongside the corresponding damage signatures on bone remains.

Past and current research has a strong focus on developing methodologies to identify both hafting and projectile use in the Palaeolithic stone tool record. This has included experimental work, ethnographic studies, use wear, residue identification, edge damage distribution and morphometric analyses (Boeda et al. 1999; Bird et al. 2007; Rots 2010, 2016; Iovita 2011; Sisk and Shea 2011; Hardy et al. 2013; Iovita et al. 2014; Chacón et al. 2016). However, their methodological validity and interpretive strength are all subject to ongoing debate (Pargeter 2011; Rots and Plisson 2014; Iovita and Sano 2016; Coppe and Rots 2017). Therefore, while claims for Neanderthal projectile technologies are frequent (Callow and Cornford 1986; Boeda et al. 1999; Hardy et al. 2001, 2013; Mussi and Villa 2008; Churchill et al. 2009; Rots 2009; Villa et al. 2009; Soressi and

Locht 2010; Lazuén 2012; Rios-Garaizar 2016), many aspects remain debated and require further contextualisation.

In contrast to this large body of literature on Middle Palaeolithic projectile damage to lithic material, studies on its related bone damage signatures are much more limited. Based on the recent record a late onset for the use of stone-tipped spears has been proposed based on the near absence of projectile impact marks (PIMs) caused by stone-tipped weapons in Middle Palaeolithic faunal assemblages, especially in contrast to later periods (Gaudzinski-Windheuser 2016). Even though the methodology for identifying hunting lesions based on fracture patterns and surface modifications is rather recent (Gaudzinski-Windheuser et al. 2018), lesions with and without embedded stones have been recognised by archaeologists and zooarchaeologists for decades (e.g., Rust 1943). Thus, the scarcity of hunting lesions throughout the Middle Palaeolithic still requires an adequate explanation.

Therefore, the aim of this paper is to explore the relationship between the frequency and significance of hunting lesions produced using trusting spears or launched as javelins by spear thrower in a highly monitored experimental setting. Results were contextualised against the background of the poorly understood nature of Palaeolithic hunting trauma and the results were discussed within the broader context of Neanderthal behaviour.

Background: The Enigma of Palaeolithic Hunting Trauma in Bones

Archaeological Evidence

Bones have the potential to preserve direct evidence of projectile hunting through bone lesions, traumata or embedded weapon tips. Their appearance in the archaeological record is well-documented from the Late Upper Palaeolithic onwards (Table 1) and here could be linked to the increased use of bow and arrow technologies (Moirenc et al. 1921; Noe-Nygaard 1974; Bratlund 1990, 1991; Milo 1998; Morel 1998; Boeda et al. 1999; Münzel and Conard 2004; Zenin et al. 2006; Letourneux and Pétillon 2008; Nikolskiy and Pitulko 2013; Gaudzinski-Windheuser 2016; O'Driscoll and Thompson 2018; Wojtal et al. 2019; Синицын et al. 2019, Sano et al. 2019). However, potential projectile impact wounds from Lower, Middle and early Upper Palaeolithic contexts are sparse and several well-known examples remain disputed, mainly from a taphonomic perspective (see Gaudzinski-Windheuser 2016 for a discussion of Boxgrove and Umm el Tlel).

Currently, the best studied and contextualised examples come from the Eemian site of Neumark-Nord 1 (Germany), where two impact wounds caused by wooden thrusting spears, were identified on two fallow deer skeletons (Table 1 Gaudzinski-Windheuser et al. 2018). Besides on animal bones, puncture wounds have also been identified on Neanderthal fossils (Churchill et al. 2009).

It is clear that several factors can affect both the occurrence and preservation of different types of hunting trauma, including hunting technology, anatomical portion and bone element, subsequent butchering and processing of the animal carcass and overall site taphonomy (bone surface preservation, fragmentation). Furthermore, the morphology of these hunting lesions can vary and various types have been defined (e.g.,

Table 1 Reported projectile impact marks on Lower, Middle and Upper Palaeolithic faunal remains; also included African Middle Stone Age examples (see Gaudzinski-Windheuser 2016 for detailed overview of projectile lesions in the Palaeolithic record)

Site	Region	Age (ka BP)	Lithic entity	Impact wound				Proposed hunting technology	Main reference
				Nr	Species	Bone element	Embedded lithic		
Boxgrove	UK	ca. 500	Acheulean	1	horse	scapula	no	untipped wooden spear	Roberts, 1999
Swanscombe	UK	ca 400	Acheulean	1	red deer	scapula	no	untipped wooden spear	Smith, 2010
Pinnacle Point 13B	South Africa	ca. 98-91	MSA	3	size 3 mammal	vertebral centrum	yes	stone tipped spear	O'Driscoll and Thompson, 2018
		ca. 98-91			size 3 mammal	cervical vertebra	yes		
		ca. 174-153			size 3 mammal	rib	no		
Klasies River Mouth	South Africa	ca. 100-85	MSA	2	giant extinct buffalo	cervical vertebra	quartzite fragment	stone tipped spear	Milo, 1998; O'Driscoll and Thompson, 2018
Neumark-Nord	Germany	ca. 125	Middle Palaeolithic	2	fallow deer	pelvis	no	untipped wooden thrusting spear	Gaudzinski-Windheuser et al., 2018
					fallow deer	cervical vertebra	no		
Shanidar	Iraq		Mousterian	1	Neanderthal	rib	no		Churchill et al., 2009
Umm el Tlell	Syria	ca. 50	Levantine Mousterian	1	wild ass	vertebra	Levallois point	stone-tipped spear	Boëda et al., 1999
			Lower and Middle Palaeolithic projectile impact marks	11					
Kostěnki 14	Russia	39	Upper Palaeolithic	1	mammoth	rib	no	ivory point	Синицын et al., 2019
Kokorevo I	Russia		Upper Palaeolithic	1	bison	scapula		no	Abramova, 1982
Combe Buisson	France		Aurignacian	1	large ungulate	unknown	osseous		Moirenc et al., 1921
Yana	Russia	29-27	Upper Palaeolithic	4	mammoth	pelvis & scapula	yes	stone tipped and osseous points	Nikolskiy and Pitulko, 2013

Table 1 (continued)

Site	Region	Age (ka BP)	Lithic entity	Impact wound				Proposed hunting technology	Main reference
				Nr	Species	Bone element	Embedded lithic		
Hohle Fels	Germany	29	Early Gravettian	1	cave bear	vertebra	yes		Münzel and Conard, 2004
Krakow Spadzista	Poland	25-24	Gravettian	1	mammoth	rib	yes	stone tipped spear	Wojtal et al., 2019
Combe Sauniere	France	19	Solutrean	1	horse	scapula	yes		Castel, 1999
La Garna	Spain		Magdalenian	1	horse	mandible	yes		Arias Cabel et al., 2005
Schussemquelle	Germany		Magdalenian	1	reindeer	scapula	yes		Schuler, 1994
Veyrier	France		Magdalenian	1	reindeer	scapula	no		Sauter, 1985
Isturitz	France	14-18	Upper Magdalenian	1	medium-sized ungulate	rib	no	hafted osseous point	Letourneux and Petillon, 2008
Lugovskoe	Russia	ca.16	Upper Palaeolithic	1	mammoth	vertebra	yes		Zenin et al., 2006
San Teodoro	Italy	ca. 14-12	Epigravettian	1	human	pelvis	triangle fragment	bow and arrow	Bacheci et al., 1997
Meiendorf	Germany		Late Upper Palaeolithic	5	reindeer	variable	yes		Bratlund, 1990
Stellmoor	Germany		Late Upper Palaeolithic	32	reindeer	variable	yes	bow and arrow	Bratlund, 1990
Grotte du Bichon	Switzerland		Final Upper Palaeolithic	1	brown bear	vertebra	yes		Morel, 1998
			Upper Palaeolithic projectile impact marks	53					

notches, punctures, perforations) (Smith 2003; Letourneux and Pétillon 2008; Leduc 2014; O'Driscoll and Thompson 2014, 2018; Gaudzinski-Windheuser et al. 2018). To clarify the causal factors and general characteristics of projectile impact wounds experimental methodologies have been developed.

Experimental Studies

While experimental work in relation to Palaeolithic hunting technologies has predominantly focussed on identifying impact damage on lithics, a series of studies has focussed on the bone damage instead. Most of these focus on specific research questions in relation to a particular weapon type and/or delivery systems and often have a focus on more recent time periods (e.g., Paleoindian, Mesolithic, osseous UP technologies) (Huckell 1982; Fischer 1985; Frison 1989; Cattelain 1997; Geneste and Maury 1997; Knecht 1997a, b, c; Letourneux and Pétillon 2008; Leduc 2014; Fullagar 2016; Iovita and Sano 2016; Langley 2016; Marreiros et al. 2016; Milks et al. 2016a; Rots 2016). Whilst these studies provide detailed data, methods are often varied and therefore comparisons or integrations are difficult. While much focus has been on documenting the basic PIM characteristics (location, size, shape, healed/unhealed, number), studies establishing links with specific hunting methods and technologies are still in their infancy.

Studies of relevance to Middle Palaeolithic hunting technologies can be divided into two categories; those focussing on lesions left by untipped wooden spears and those that incorporate Levallois point morphology (Table 2). The latter has been applied to a wide range of target types (not always containing a bone component) and delivery methods, resulting in varying velocities at impact.

However, current methodologies and approaches do not fully synthesize and integrate the lithic and faunal data (see Table 2); many studies have been interested in a single material category (lithic or bone) or the formation of a specific characteristic (diagnostic impact fractures [DIFs], projectile impact marks [PIMs]). Sometimes, experimental studies incorporate both materials and attempt to make inferences about hunting technology through the experimental replication of a related hunting lesion (e.g., O'Driscoll and Thompson 2014). However, such approaches can often ignore a basic tenet of lesion formation, specifically, that the relevant proxies are not only the properties of the impacting object (lithic projectile) but also of the target medium (bone).

In this paper, we will argue that to identify more accurately the use of projectiles within the archaeological record requires an experimental framework that considers the interaction and specific properties of both the object (lithic projectile) and the target medium (bone). With this approach, we will have a more comprehensive understanding of the conditions under which both lithics and bones fracture, their corresponding signatures and their interpretative potential.

Materials and Methods

To ensure comparability in terms of parameters measured and data recorded, the replicative setup used the same replica Levallois point as those employed in our

Table 2 Overview of the main experimental studies with untipped wooden and Levallois tipped spears (see O'Driscoll and Thompson 2014, Table 2 for additional experimental setups)

Weapon type and delivery method	Reference	Spear weight (g)	Velocity (m/s)	Target	Impact damage studied	
					Lithic	Bone
Untipped wooden spear						
Thrusted and hand thrown	Smith 2003	not recorded	not recorded	two lamb carcass	n/a	yes
Thrusted	Milks et al. 2016a,	752 and 806	2.8–6.3	ballistic gelatin	n/a	n/a
Thrusted	Gaudzinski-Windheuser et al. 2018	3130	2.2–6.8	red deer scapulae/pelvis in ballistic gelatin	n/a	yes
Levallois tipped spear						
Calibrated crossbow	Shea et al. 2001	not recorded	1.0–1.5	two goat carcasses	yes	no
Calibrated crossbow	Churchill et al. 2009	ca. 530	7.8–13.4	two dressed pig carcassess (focus on ribs)	no	yes
Bow and arrow	Sisk and Shea 2009	not recorded	not recorded	leather covered archery target and skin covered rack of ribs	yes	no
Calibrated crossbow	O'Driscoll and Thompson 2014	not recorded	21.2–26.4; 33.3–36.1	skinned and gutted lamb carcass	no	yes
Compressed air gun	Iovita et al. 2014	266	7–30	composition of bone-like plates, ballistic gelatin and leather	yes	yes
Pendulum	Iovita et al. 2016	10-60 kg simulating body weight added to thrust	1.1–2.7	composition of bone-like plates, ballistic gelatin and leather	yes	no
Thrusted	this study	ca. 625	2.3–4.7	two wild boar carcasses	yes	yes
Spearthrower	this study	ca. 150	14.4–27.3	two wild boar carcasses	yes	yes
Tipped and untipped spears						
Calibrated crossbow	Wilkins et al. 2014	ca. 585 (untipped) and 556 (tipped)	8.9–9.4	gelatin	no	n/a

previous controlled experiments (Iovita et al. 2014, 2016; Schlösser 2015) (see Table 3). Though small differences were measurable between the specimens, the coefficients of variation (0.009 (length), 0.03 (width), 0.04 (thickness), and 0.04 (weight)) are very low. All points were cast in soda-lime glass by the Meka Glas GmbH in Kaufbeuren, based on a plaster cast made in the Restoration Laboratory of the Leibniz Research Institute for Archaeology (former Römisch-Germanisches Zentralmuseum).

Alongside these glass points, an experienced knapper (Michael Genutt) produced comparable Levallois points from obsidian with similar dimensions (see Table 3). Whilst these were originally introduced for easier detection of secondary fracture characteristics (Wallner 1939; Hutchings 1999, 2011, 2015; Sahle et al. 2013; Iovita et al. 2016; Schlösser 2015), it also offers the opportunity to compare projectile impact marks between the different material types.

All points were hafted onto furrowed wooden foreshafts (dimensions 100 mm × 20 mm) using beeswax to provide a stable connection between point and foreshaft, and an easy way to remove points for future analysis. In addition, this hafting medium has been identified archaeologically (d'Errico et al. 2012) and used in previous experiments (Stodiek 1993; Iovita et al. 2014; Kozowyk et al. 2017). Foreshafts were all identical in weight and dimensions and were only replaced when broken or no longer usable.

Foreshafts were attached to a machine-made wooden main shaft using a large metal screw, attached to the foreshaft and fixed with glue (Baales et al. 2017). For the thrusting experiment, the main shaft had dimensions of 210 cm and a diameter of 2.7 cm, weighing approximately 625 g (see Schlösser 2015 for further details). For projectile experiments, the main shaft had a similar length (210 cm) with a smaller diameter (1.3 cm) and weighing 150 g (without foreshaft and tip) and containing a cavity to hook a spear-thrower at its base. In addition, to provide highly controlled flight behaviour, it was necessary to fletch the dart.

Two freshly killed female wild pigs (ca. two years old) were used as targets with experiments conducted over two days; this required more than one target, and *rigor mortis* had passed at the time of each experiment. Under German law, it is forbidden to sell dead animals with intestines inside so both targets were stuffed with materials (hay, straw, cattle intestines) to replicate the resistance of the original

Table 3 Dimensions and weight for different components used in construction of spears used during replicative experiments; modified from Schlösser (Schlösser 2015, Table 1)

Projectile component	Dimensions (mm)	Weight (g)
Glass point (mean)	64.5 × 36.5 × 6	17.5
Obsidian point (mean)	66.3 × 38.6 × 9.6	21.7
Foreshaft	100 × 20	18.5
Thrusting spear shaft	2100 × 27	660
Dart shaft	2100 × 13	185
Hafted glass point (mean)	125 × 36.5 × 20	39.5
Hafted obsidian point (mean)	125 × 38.6 × 20	45.4

Fig. 1 Setup for spear-throwing experiment no. I

internal organs. However, it is important to emphasize that all hide, muscle, flesh and bones remained intact for both individuals.[1]

The target boars were fixed with ropes and suspended from a metal frame at a height of around 1.5 m for the spear throwing experiments and around 1.2 m for the thrusting experiment with each target stabilised using Styrofoam and straw bales (see Fig. 1). The target heights were selected to permit an element of control for both the flight path and stabbing path allowing for the more accurate recording of the velocity (see Schlösser 2015 for further details).

Each type of projectile technology (thrown vs. thrusted) was only used on one body side of the boar to ensure, first, that the target did not become too damaged and second to ensure easier identification of resulting damage. For the spear throwing, individuals with experience in European spear thrower competitions were invited, to ensure that the achieved velocities were within an actualistic range (see Table 2). The speed of both technologies was recorded using two single-lens reflex cameras set on video mode with 50 frames per second and 25 frames per second, respectively (see Fig. 1 and Schlösser 2015). One camera was positioned at the release point (Nikon D7000/25 fps), covering a field of about four meters and recording the launch. The second camera (Canon EOS 600D/50 fps) was positioned at target entry and again

[1] During the butchery of the boar from the second experiment, we noted significant damage to the right humerus and upper limb bone from the hunter's shot; no other damage from hunting was noted and this was thoroughly documented and wounds discounted in subsequent analyses.

Table 4 Definition of PIM types recorded per element during experiments; based on O'Driscoll and Thompson (2014) and Gaudzinski-Windheuser et al. (2018)

PIM type	Definition
Striation/drag	Linear mark caused by the dragging of lithic impact on bone surface
Notch	Projectile impact on the edge of a bone
Pit	Depression on bone surface
Perforation	A hole made by puncturing by projectile impact
Fracture	Linear fracture caused by bone cracking
Bevelling	Bone bevelled due to the direction of impact from projectile
Cracks	Linear cracks that radiate from impact point
Embedded lithic	Parts of the projectile tip embedded in bone

covered a field of about four meters. To avoid optical distortion, both cameras were set about 15 m away from the path to be recorded. The launch camera was skipped for the thrusting experiment because the recorded field could only be covered by one camera (Schlösser 2015). Furthermore, an accelerometer was attached to the spear close to the foreshaft to evaluate what occurred during impact with the carcass. In addition, this was coupled with a velocity measuring instrument beneath the boar to provide a first impression of the velocities involved.

Projectiles were thrown from between 8 and 10 m from the carcass[2] with exact distances recorded for each shot. This distance permitted the highest probability of both striking the target whilst simultaneously allowing for the projectile to reach maximum velocity. Spears were thrusted from 1 to 2 m from the carcass with minimal run-up and were thrust over- and underarm, in this first attempt without twisting.

For each shot that impacted on the carcass, a range of preliminary visual attributes was recorded:

1. Projectile delivery method
2. Lithic point number
3. Shot number with that particular lithic
4. Velocity at impact
5. Location of impact
6. Type of hit: did point impact on bone or just lodge within the muscle mass
7. Visible macro-damage to lithic point
8. Visible macro-damage to skeletal element

Once the experiments were completed, the remains were butchered and recorded by two of the authors (GMS, ESN) in order to accurately reconstruct how the damage to the skeleton related to specific lithic point and shot identified by throw number. While these authors have previous experience with butchery, any incidental modifications were noted and recorded to avoid confusion with subsequent analyses. Both carcasses were defleshed and degreased at MONREPOS Archaeological Research Centre, and all projectile modifications were recorded using a standardized methodology (Gaudzinski-Windheuser et al. 2018) (see Table 4).

[2] If the distance changed, this was recorded to ensure the accurate calculation of velocity and kinetic energy.

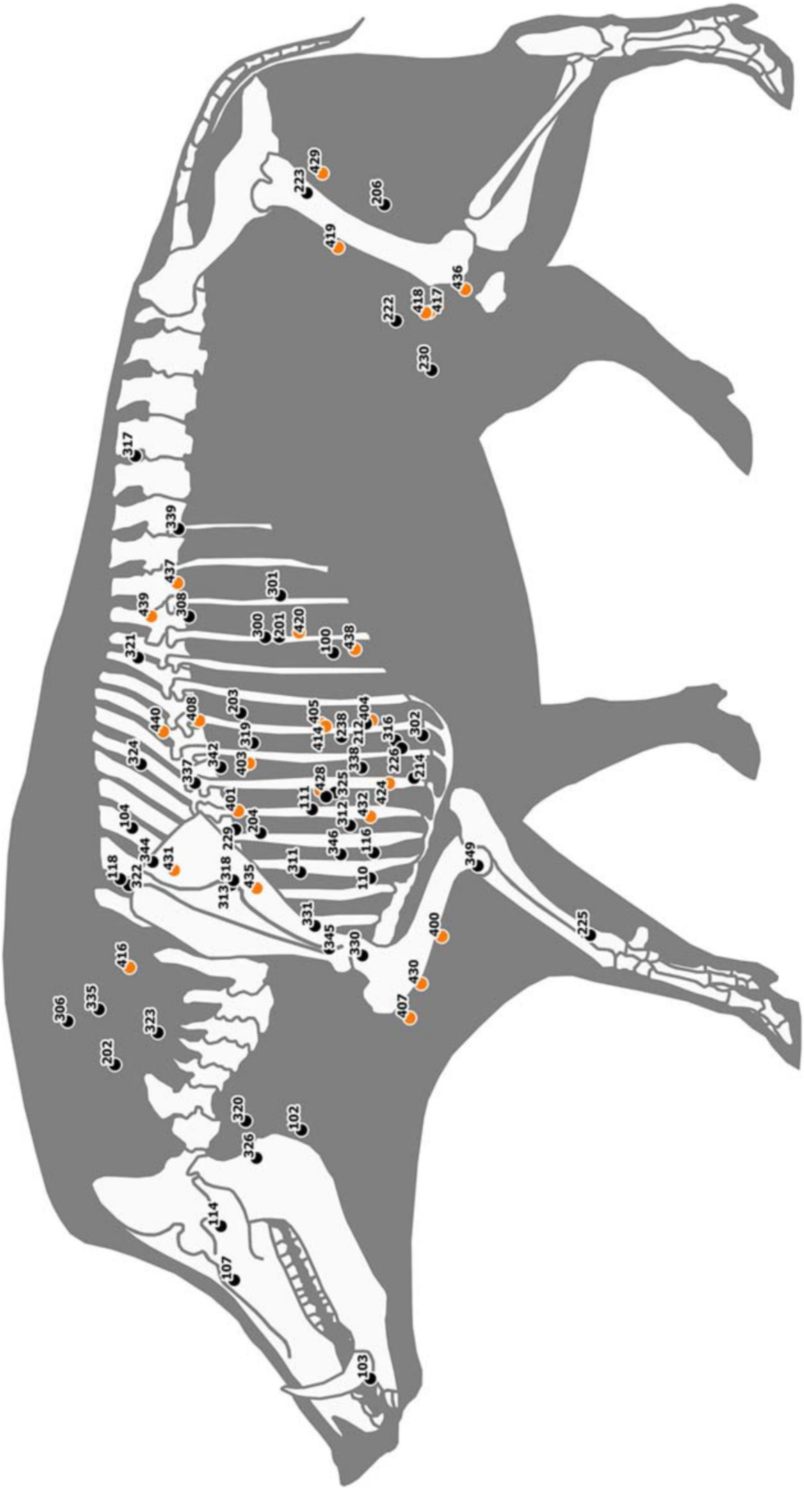

Fig. 2 Location for all hits on carcasses record during throwing (black) and thrusting (orange); experiments; numbers refer to specific shot numbers (exp. 1 = 100; exp.2 = 200; exp.3 = 300; exp. 4 = 400); and all shots have been located using GIS and are shown on the left hand side for ease of comparison

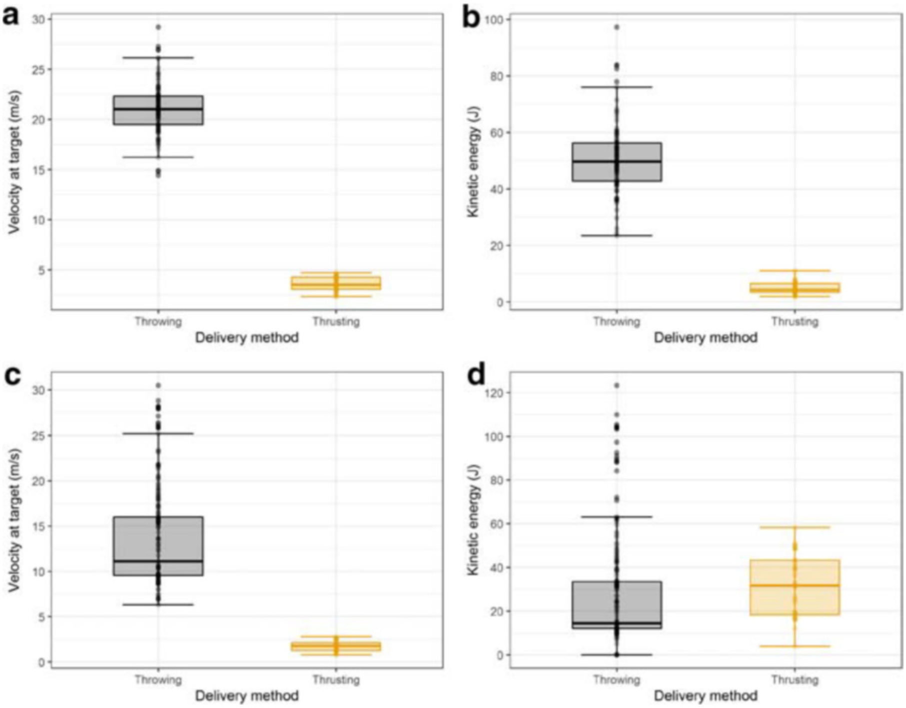

Fig. 3 Boxplots of velocity at target (m/s) (left) and kinetic energy (J) (right) for each delivery method during both the replicative (**a** and **b**) and controlled experiments (**c** and **d**); black line indicates median

Furthermore, the spear points were analysed, and both macro fracture and secondary fracture characteristics (Wallner lines) were recorded and analysed (NMB) (Schlösser 2015). Such an analysis of crack front velocities was used to test whether, for these replicative experiments, specific weapon delivery systems could be distinguished (Hutchings 2011). In a final step, the results from these replicative experiments were compared to those from previously published controlled experiments (Iovita et al. 2014, 2016).

All analyses were conducted in R (R Core Team 2018), and figures were produced using the ggplot2 package (Wickham 2016) except Fig. 2, which was produced using QGIS 3.4 (QGIS Development Team 2009).

Table 5 Number of hits recorded on carcasses for each delivery method during each experiment and the proportion of projectile impact marks (PIMs) from hits (not the total number of shots)

Delivery	Miss	Hit	Total shots	%Hit	Bone elements with PIM	%PIM from hits
Throwing	53	56	109	51.4	18	32.1
Thrusting	18	25	43	58.1	8	32
Total	71	81	152	66.4	26	32.1

Table 6 Total number of points used for each material type during each experiment and number of points for each raw material exhibiting impact fractures (data compiled from Tables 2 and 3; Schlösser 2015)

Delivery method	Glass (fractured)	Obsidian (fractured)	Total points
Projectile	10	14	46
Thrusting	0	11	15
Total	10	25	61

Results

Velocity and Kinetic Energy

In total, 152 shots were undertaken over all experiments with the velocity of the projectile at target entry recorded for 142 shots (93.4%) and with a high proportion of data recorded for both projectile (92.7%) and thrusting (97.7%) experiments (see Fig. 2). The velocities for thrown spears range from 14.4–29.2 m/s (mean 21.2 m/s) while thrusting ranged between 2.3–4.7 m/s (mean 3.5 m/s) (Fig. 2). These velocities all fall within the ranges provided for other experimental studies, especially for the velocity values for the thrusting experiments (Table 2). These figures are consistent with those produced in previous experiments by one of the authors (RI) for both hand thrown spears (6–31 m/s; mean 14.1 m/s) and thrusted spears (1–2.8 m/s; mean 1.8 m/s) (Iovita et al. 2014, 2016) (see Fig. 3).

Both velocity data and calculated kinetic energy values illustrate a clear separation for both delivery options (throwing vs. thrusting) with very few outliers. The kinetic energy of the spear was computed as:

$$KE = \frac{1}{2}mv^2$$

where m is the mass of the spear and v is the velocity of the spear tip before impact. Kinetic energy for thrown projectiles ranged between 23.4–97.3 J (mea$n = 51.8$ J) while kinetic energy generated during the thrusting experiments ranged from 1.9–8.3 J (mean = 4.7 J) (see also Gaudzinski-Windheuser et al. 2018 for discussion of the additional force applied during spear thrusting).

Frequency of Hits and Damage

Despite a relatively large proportion of hits on the carcass ($n = 81$; 53.4%) over both experiments, this resulted in a relatively low number of bone elements associated with PIMs ($n = 26$; 32.1%) for both delivery methods (Table 5).[3] The majority were identified from the projectile ($n = 18$) compared to thrusting ($n = 8$).

[3] Assigning PIMs to specific shot number was complicated by the position and reuse of the carcass during the replicative experiments. Furthermore, repeated strikes in the same region often made it more difficult; future experiments will adopt an element grouping approach (see subsection 5.1).

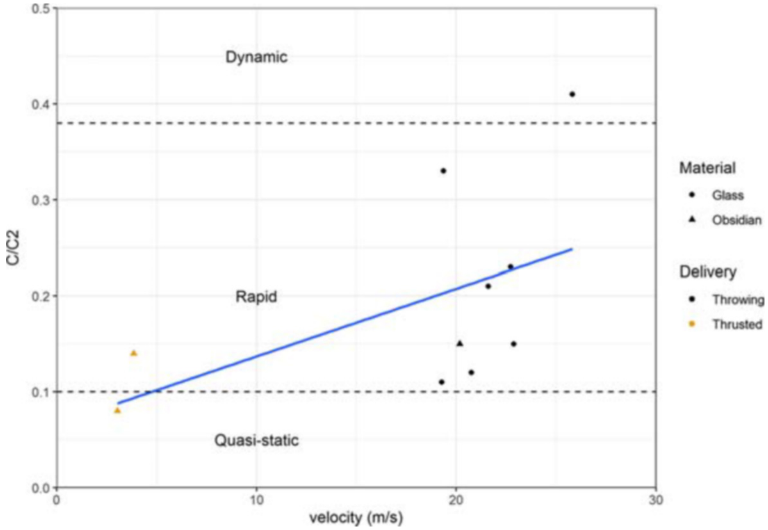

Fig. 4 Plot of C/C2 ratios against velocity at target entry with different shapes illustrating different delivery methods; the lines illustrate defined loading rate ranges, redrawn after Schlösser 2015, Tab19; the loading rate ranges (Quasi-static, Rapid and Dynamic) are taken from calculations from (Hutchings 2011)

This discrepancy between carcass hits and recorded PIMs could have resulted from at least two complementary factors. Firstly, the variation in skill level of the participants for both throwing and thrusting experiments; those undertaking the projectile experiments had prior experience with the use of such prehistoric technology, while the experience of participants for the thrusting experiments was more varied. Thus participants in the projectile experiments had potentially greater control over the flight and impact of the spear point, increasing the likelihood of carcass hit and PIM formation (Milks et al. 2016a). Secondly, both the higher velocities and increased kinetic energy undoubtedly influenced the ability of the spear point to penetrate the soft tissue and muscle of the carcass and impact on the bone (Wilkins et al. 2014; Milks et al. 2019). Thus, carcass

Table 7 PIM recorded per element during experiments (percentage of PIMS by bone element with PIM, see Table 5); based on O'Driscoll and Thompson (2014) and Gaudzinski-Windheuser et al. (2018)

PIM type	Throwing	% PIM element	Thrusting	% PIM element
Striation/drag	2	11.1	1	12.5
Notch	14	77.8	4	50
Pit	2	11.1	2	25
Perforation	1	5.6	1	12.5
Fracture	14	77.8	6	75
Bevelling	9	50	3	37.5
Cracks	5	41.7	1	12.5
Embedded lithic	3	27.8	2	25

Table 8 Number of PIMs recorded across individual bone elements from the throwing experiments

Element	Drag	Embedded lithic	Fracture	Notch	Pit	Perforation	Total
cervical vertebra			1	1			2
vertebra			5	2			7
rib	1	1	6	11			19
scapula		1	4	3	1	2	11
humerus	1						1
radius		1	1		1		3
Total	2	3	17	17	2	2	43

strikes at lower velocities and with reduced kinetic energy may not have had sufficient energy remaining to impact on the bone causing PIMs.

In contrast, lithic data from these replicative experiments illustrate an opposite pattern, with a lower proportion of points from the projectile experiments exhibiting DIFs (Table 6). Overall, 52.2% of the thrown points (24 out of 46) and 73% of the thrusted points (11 out of 15) that hit the target exhibit impact fractures. Most common are longitudinal breaks ($n = 17$), transversal and snap fractures ($n = 10$), lateral breaks ($n = 7$) and spin-offs ($n = 5$) (see Schlösser 2015 for further details).

Of these fractured pieces, only a small proportion ($n = 10$; 28.6%) were suitable for further analysis of secondary fracture characteristics in an attempt to assign these to a specific weapon delivery system. There appears to be little separation based on C/C2 ratios, with only one value from the spear-throwing experiments within the dynamic range and, similarly, only one value from the thrusting experiments within the quasi-static range. The remaining values were spread throughout the rapid range (Fig. 4).

Types of Bone Damage

The types of PIMs recorded on bones from both experiments were similar and are detailed in Tables 7, 8 and 9 (see Table 4 for PIM definition). In total, across all the experiment, 26 individual bone elements exhibited PIMs (Tables 5 and 7). Multiple impacts on the same skeletal elements during these experiments frequently caused the formation of multiple PIMs on the same element (throwing $n = 43$; thrusting $n = 16$). Tables 8 and 9 provide a detailed breakdown by element of the different PIM types. For

Table 9 Number of PIMs recorded across individual bone elements from the thrusting experiments

Element	Drag	Embedded lithic	Fracture	Notch	Pit	Perforation	Total
vertebra	1	1			1		3
rib		1	5	3	1		10
scapula			1	1		1	3
Total	1	2	6	4	2	1	16

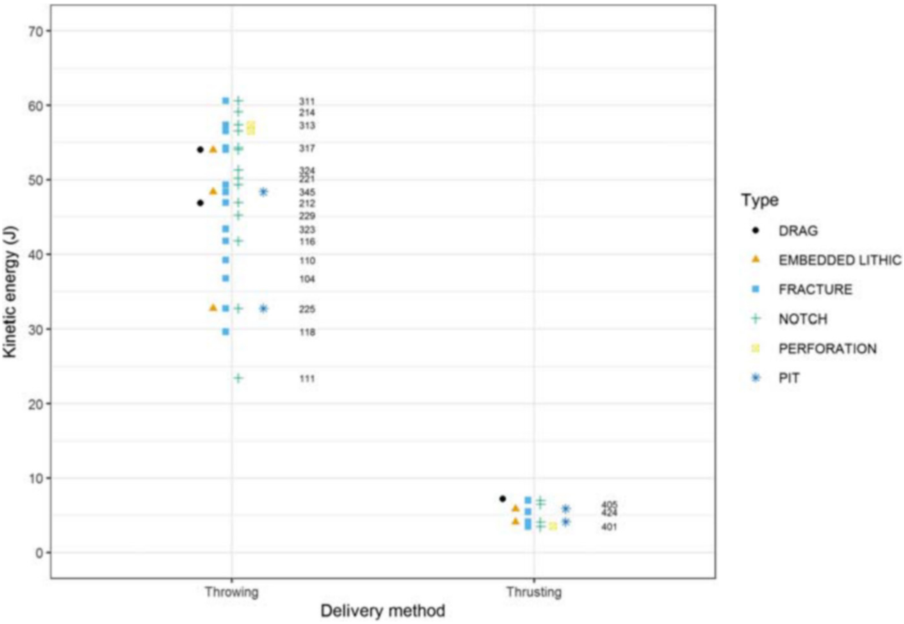

Fig. 5 PIMs recorded throughout replicative experiments plotted by delivery method and kinetic energy (annotated numbers are individual shot numbers)

the throwing experiments, the most common damage signatures were fractured elements and notches (79.1%; $n = 34$) caused by projectile impacts on or close to the edge of bone or passing between two adjacent elements (e.g., ribs). Fractured and notched elements were also recorded in the thrusting experiment though in a lower quantity. Both throwing and thrusting experiments produced drag marks, perforations and embedded lithics across a range of kinetic energies (Fig. 5). The smaller number of elements with PIMs from the thrusting experiment, compared to the throwing experiment, currently makes a more quantitative comparison difficult (see subsection 5.1).

The PIMs recorded in these experiments are consistent with those reported in other experiments, particularly in relation to the perforated scapula (Fig. 6) and embedded lithics (Fig. 7). Overall, the PIMs recorded throughout these replicative experiments are comparable between delivery methods and similar to bone breakage resulting from other taphonomic agents, including human butchery activities (Fig. 7 radius spiral fracture; rib fracture). The formation of a particular PIM is dependent on the condition of the bone (fresh vs. dry) and type of element impacted (Lee Lyman 1994; Smith 2003; Fernandez-Jalvo and Andrews 2016).

Link Between Bone Damage and Other Factors

These replicative experiments have illustrated that the formation of PIMs on bones and even lithic DIFs result from a complex interplay of various agents. Therefore, it is difficult to fully account for or control these factors when constructing experimental protocols and drawing inferences and conclusions about projectile technology (including this study) and broader patterns of Neanderthal subsistence behaviour (Smith 2003;

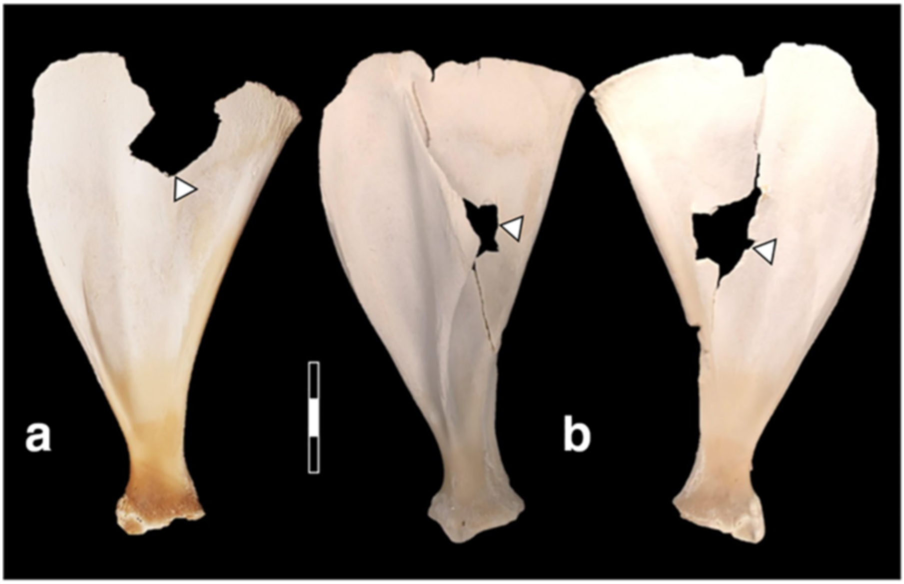

Fig. 6 Scapula fragmentation from thrusting (**a**) and throwing (**b**) experiment; note visual similarities in perforation outline (due to the use of same lithic point) but more extensive cracking and fragmentation in scapula from throwing experiment

Iovita et al. 2014; O'Driscoll and Thompson 2014, 2018; Rots and Plisson 2014; Wilkins et al. 2014). Using controlled laboratory setups allows for the control of specific factors to isolate and understand the intersection of key variables related to the formation of a particular bone modification of interest, in this case PIMs. Similarly, replicative setups can also be used to reflect on the controlled experiment, especially in cases where both experimental settings diverge in key components from each other, for example as in our case by the target material. Both setups provide comparable and complementary data to try to answer questions from the archaeological record.

Figure 8 illustrates the different PIMs recorded for a series of replicative experiments (this study) and lab based experiments using bone plates (Iovita et al. 2014, 2016); the figure compares three different types of recorded PIMs (drag mark, pit, fracture)[4] against calculated kinetic energy, delivery method and impact angle (lab experiments only). Both experiments illustrate a higher proportion of impact marks during the throwing experiments due in part to the higher velocities and kinetic energy but, potentially, also the skill of the participants (see subsection 4.2). The reduction in the number of fractured elements during replicative experiments is also likely related to a greater number of variables involved in hitting the target. It is possible that the absence of fractured elements during the thrusting experiments resulted from reduced kinetic energy, though further experimental work is necessary to quantify and compare across species, element and delivery method (see subsection 5.1).

Another interesting trend is the impact angle of the point relative to the target, which could only be assessed in the laboratory experiments. While the frequency

[4] These three types of PIMs were recorded in the lab experiments and in order to ensure comparability these similar damage signatures were selected from the PIMs recorded for this study.

Fig. 7 Examples of PIMs from replicative experiments; **a** spirally fractured radius with embedded glass point from throwing experiment (illustrates origin of fracture), **b** thoracic vertebrae with embedded obsidian tip from thrusting experiment and **c** fractured rib with notch from throwing experiment

of shots for the laboratory throwing experiments is highest at 90° and lowest at 30°, some interesting trends for comparison were identified. During the throwing experiment, cut-mark like drags were only present at lower impact angles (30° and 45°) and in relation to a range of kinetic energy values, though always less than 40 J (Table 10). As the impact angle was increased (60°, 75°, 90°) the proportion of drags and pits formed on the bone plates decreased while the number of fractured plates increased. At the higher impact angles, the plate always fractured even at lower kinetic energy (40 J >); by contrast, at an impact angle of 45° fractured plates were only recorded at relatively high kinetic energy (above 40 J) with none whatsoever recorded at the lowest impact angle (30°).

This contrasts to the lab-based thrusting experiments where no drag marks were identified though fractured and pitted plates were recorded across the range of kinetic energy values. The absence of comparative data for different impact angles (compared to throwing experiment), currently limits our comparative and interpretive potential (see subsection 5.1).

Furthermore, data from the replicative experiments produce considerably fewer comparable PIMs for both delivery methods (Fig. 8). Both delivery types produced

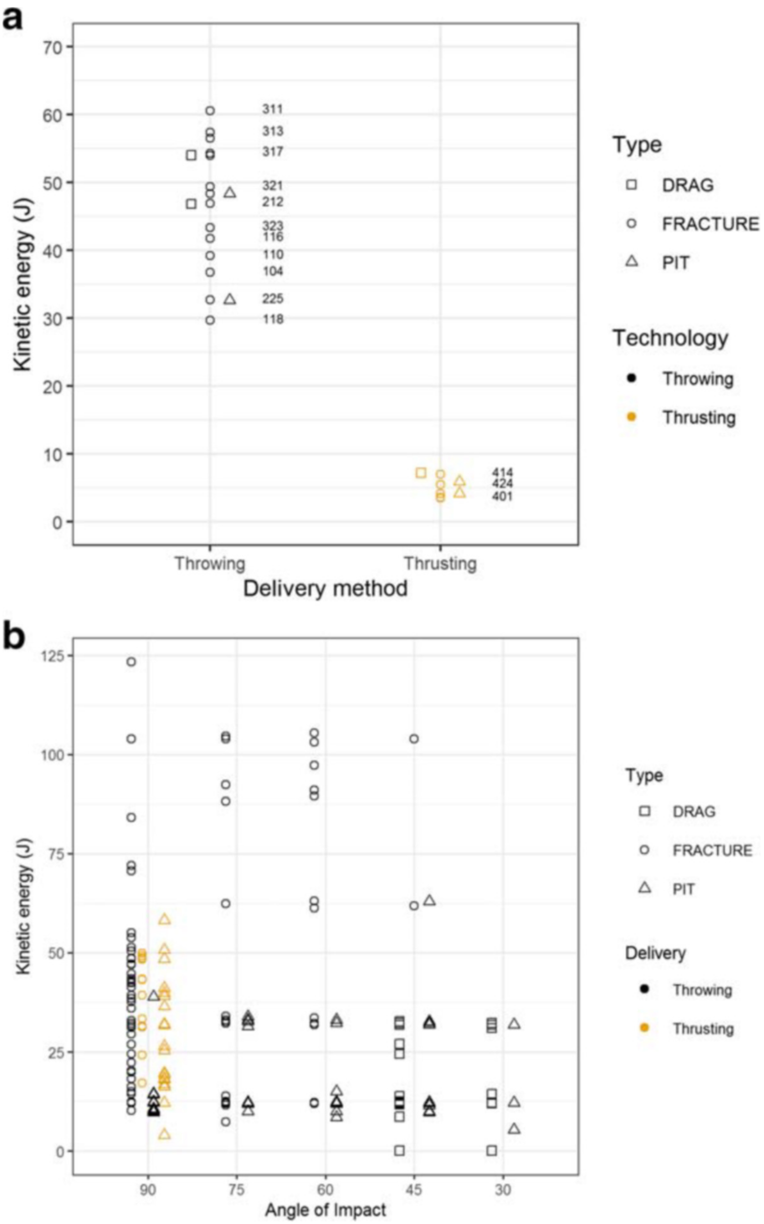

Fig. 8 Comparison of PIMs recorded on **a** replicative wild pig experiments (this paper) and **b** controlled experiment bone plates (Iovita et al. 2014) plotted against kinetic energy (J), delivery method and impact angle [only for lab-based experiments]; square: drag; circle: fracture; triangle: pit. Coloured by delivery method. Note this does not include the total number of PIMs for both types of experiment but incorporates comparable PIM types. Shot numbers included for replicative experiments (**a**)

drags, perforations and fractures though these were less common in the thrusting experiments. The range of kinetic energy and small sample size make further comparisons with the lab-based dataset difficult.

Table 10 Impact angle and total PIMs for lab-based throwing and thrusting experiments; numbers in parentheses are percentage of PIMs relative to total shots

Impact angle	Total shots	Total PIMs	Drag	Pit	Fracture
30°	22	12	9 (40.9%)	3 (13.6%)	0
45°	44	39	22 (50%)	14 (31.8%)	3 (6.8%)
60°	35	34	0	20 (57.1%)	14 (40%)
75°	35	35	0	14 (40%)	21 (60%)
90°	98	75	0	30 (30.6%)	45 (45.9%)
90° (thrust)	42	38	0	24 (57.1%)	14 (33.3%)
Total	276	233	31	105	97

These replicative experiments using stone tipped weapons have produced identifiable PIMs including embedded lithics, notches and drag marks, both with bevelling indicative of directionality. However, these PIMs cannot be used to distinguish definitively between delivery systems. Further systematic work integrating lithic and faunal data from both experimental and archaeological data sets is required.

Discussion

Further Work

Further experimental work is necessary to fully understand the formation of DIFs and PIMs, including both controlled and replicative setups.

These experiments have illustrated that the formation of lithic fractures and projectile impact marks on bones are the result of a complex interplay between the kinetic energy and how this is dispersed through a target medium (see also Coppe et al. 2019). In these experiments, the target medium was a carcass composed of muscle and bone, only some of which preserve in the archaeological record. In order to more fully understand and recognise lithic and faunal fracture patterns resulting from projectiles, we need the development of a methodology that investigates not only the launch system and projectile type but thoroughly and consistently uses a comparable target medium.

While the experimental setup allowed the carcass to be in a relatively natural anatomical position, the suspension (Fig. 1) provided limited resistance compared to a live standing animal. Such limited resistance meant that during these experiments, especially those using a thrusting motion, the carcass was pushed away. This could have affected the kinetic energy recorded between these different delivery systems; future experiments should attempt to provide a setup that provides more resistance and replicates, as closely as possible, a realistic, anatomical setup to provide more accurate kinetic energy values. In order to more fully understand how differences in kinetic energy relate to PIM formation requires a more systematic comparative approach; ideally this would standardise the velocity, species and body parts in order to provide large scale quantitative data for comparison of PIM type and formation and how these relate to kinetic energy and, potentially, delivery system (Coppe et al. 2019).

Future experiments should focus on more manageable body portions to understand, in more detail, how different bone elements influence PIM formation in relation to different bone density and delivery methods (see Gaudzinski-Windheuser et al. 2018). Further, many of the experiments documented, including these, use relatively small-sized animals (wild boar, sheep) (this study; O'Driscoll and Thompson 2014). The faunal assemblages from Middle Palaeolithic contexts illustrate a range of species with varying body sizes and bone densities; to understand more fully PIM formation and recognition in archaeological assemblages requires detailed investigation into how variation in prey body size and bone density may affect fracture patterns.

Further work is necessary to understand the importance of location, skeletal element and impact angle in PIM formation and distinguishing different delivery methods. This could be approached through further controlled lab experiments with a standardised number of shots at set velocities (low, medium, high) (Iovita et al. 2014) for each impact angle. This would afford greater comparability of DIFs and PIMs and allow for further rigorous testing of the potential effects of both velocity (and associated kinetic energy) and impact angle. This could be applied to both hand thrown and thrusted projectiles. We also recommend for future analysis not to use complete carcasses as they result in a very limited data sample per variable, but to use a larger sample of specific animal bones embedded in gelatine (see Gaudzinski-Windheuser et al. 2018).

Furthermore, it is important to note that the velocities recorded during both our "hand launched" experiments (thrown and thrust) are considerably lower than some others in the published literature (Hutchings 2011; Wilkins et al. 2014). Nevertheless, these are consistent with most published studies and appear more representative of human capacity and as such, the damage recorded, and in some cases, absence of damage (especially on lithic points) is perhaps of more interest and importance. Further replicable experiments, both in controlled and replicative setups, will hopefully provide data to clarify these initial findings.

Palaeolithic Projectiles: Experimental and Archaeological Perspectives

Discussion surrounding the form and function of projectile technology has, to a degree, framed the debate surrounding the emergence of more complex behaviours and technologies and, tacitly at least, been suggested as a factor behind Neanderthal extinction.

The absence of unambiguous evidence for such hunting technology within the Middle Palaeolithic record has necessitated the development of novel techniques and methodologies. Many of these methodologies have focussed exclusively on the recognition of projectile or spear points through the study of lithic shape, size or DIFs (macro and microscopically) upon certain zones (Sahle et al. 2013; Iovita et al. 2014, 2016; Wilkins et al. 2014, 2015; Milks et al. 2016b; Rots 2016; Sahle and Brooks 2019). Whilst progress has been made in identification of certain signatures of lithic and tip fracture related to spear use, there still remain significant methodological problems in relating fracture types to specific projectile technology, if at all (Iovita et al. 2014; Schlösser 2015). In part, this relates to a lack of standardisation in methodologies, both archaeological and experimental, and issues of equifinality with regard to the lithic fracture pattern within the archaeological record (Rots and Plisson 2014; Wilkins et al. 2015).

The analysis of spear points from our replicative experiments illustrated the ongoing difficulty of assigning specific fracture characteristics to a particular delivery method. Schlösser (2015) illustrated that the relationship between secondary fracture characteristics and velocity at target entry were not significant for these experiments with a regression coefficient of 0.149 with $p = 0.271$ (see also Hutchings 2011; see Schlösser 2015 for further details). This demonstrates the ongoing difficulty of using the ratio of these microscopic characteristics to calculate the velocity at entry and hence associate these fractures to a specific delivery system (see Fig. 4). Taken together, these experiments illustrate the difficulty in assigning DIFs on lithic points to a weapon delivery system and raise similar questions about whether the associated PIMs are suitable for distinguishing between them (Schlösser 2015; Iovita et al. 2016; Coppe et al. 2019).

Initial analyses of bone plates from the controlled throwing experiments illustrate that impact angle influences the amount of energy transmitted into the target medium. This has, consequently, important implications for the formation of PIMs on animal bones, our subsequent ability to securely identify these and, furthermore, to assign such modifications to a specific projectile type. This observation has major implications for our interpretation of data on lithic DIFs and bone PIMs from replicative experiments, where impact angle cannot be so highly controlled. In light of such evidence, this challenges the current state of knowledge regarding the description, definition and use of both lithic DIFs, and bone PIMs to identify and differentiate projectile technology. Consequently, this has wider implications for the identification and use of projectile technology within the archaeological record.

Within the context of such replicative experiments, the PIMs identified on specific elements or bone portions are easily assignable to projectile use. However, once such modifications are examined outside this experimental framework, i.e., in uncontrolled (archaeological) contexts, such marks illustrate a degree of equifinality with other bone surface modifications (e.g., spirally fractured long bone) (Lee Lyman 1994, 2008; Fernandez-Jalvo and Andrews 2016). To identify PIMs more definitively within the archaeological record requires a combination of features such as embedded lithics, bevelling and evidence for directionality. Furthermore, the location of fractured elements combined with an absence of conchoidal fractures or carnivore tooth marks could also help to differentiate PIMs from other bone modification signatures. Finally, to more securely define and identify modifications resulting from projectile impact requires the recognition of PIM traces on anatomical groups such as on neighbouring ribs or vertebrae.

Ultimately, it may prove more problematic to use PIMs to differentiate between various projectile delivery methods (thrusting vs. throwing). The intensity of fragmentation, particularly in relation to the formation of cracks across skeletal elements, appears to illustrate a qualitative difference between hand thrown[5] and thrusted projectiles. The frequent bone fragmentation of Middle Palaeolithic faunal assemblages could lead to a decreased recognition of PIMs due to either the poorer preservation of

[5] 'hand-thrown' refers to the use of spear thrower, and further work is needed to investigate impact traces by javelins both with and without lithic points.

key areas, such as ribs or scapulae, or inability to differentiate such modifications from other agents causing fragmentation in these faunal assemblages.

Finally, while much of the debate has centred on the identification of Neanderthal lithic projectile technology, DIFs and associated PIMs, archaeologists must also consider Neanderthal use of wooden spear without lithic tips (Thieme 1997, 2005; Smith 2003; Schoch et al. 2015; Gaudzinski-Windheuser et al. 2018; Milks et al. 2019). The presence of these artefacts within the Middle Palaeolithic archaeological record and the identification of PIMs, certainly for the last interglacial (Gaudzinski-Windheuser et al. 2018), necessitate additional experimental protocols and another level of interpretive complexity (see also Coppe et al. 2019). Taken together, this suggests that Neanderthal approaches to hunting technology and subsistence varied across space and through time, which seems to be emblematic of their behavioural repertoire as a whole (Ruebens 2013; Ruebens et al. 2015).

The broader implications of these experiments illustrate the need to move beyond a static cause/effect situation in relation to the application of experimental methods to answer archaeological questions. Importantly, at the most basic level, the PIMs identified throughout these and other experiments are a function of the bone type and their condition (dry vs. fresh), which, obviously, raises issues of equifinality. Such equifinality in damage signatures, within these experiments and with other taphonomic agents, means that only the increased fracturing and cracking associated with PIMs from the throwing experiments could help distinguish between the different delivery methods (in an absence of embedded lithic points). However, the fragmentary nature of Middle Palaeolithic faunal assemblages means that distinguishing PIMs from other site formation processes and, especially, Neanderthal butchery behaviour is, at present, complicated. Indeed, we risk repeating past mistakes by continuing in an unsystematic fashion to collect data that is neither comparable nor reflects the complexity behind PIM formation in experimental settings and subsequent recognition in archaeological contexts.

Conclusion

The use of projectile technology permits the targeting of a wider variety of large- to medium-sized terrestrial game while, importantly, mitigating risk by allowing the killing of prey at a distance. Despite ample evidence that Neanderthals were skilled and proficient hunters in a range of environments and across a broad time range (Gaudzinski 1995, 1999; Steele 2004; Niven et al. 2012; Gaudzinski-Windheuser et al. 2014a, 2018; Smith 2015; Castel et al. 2017; Jaouen et al. 2019), there is an absence of either clearly identifiable projectile points or impact damage from Middle Palaeolithic contexts, compared to other time periods (Table 1) (Noe-Nygaard 1973; Austin et al. 1999; Smith 2010, 2013; Gaudzinski-Windheuser et al. 2018). Invariably, this has led to the hypothesis that the absence of both recognisable projectile technology and hunting lesions before the late Upper Palaeolithic is simply that these implements were not a regular part of hunting technology (Gaudzinski-Windheuser 2016). Such a proposal runs counter to many current perspectives on the origins and spread of lithic projectile technology and its evolutionary implications (Wilkins et al. 2012; Wilkins and Schoville 2016; Sahle and Brooks 2019).

To test these hypotheses requires the integration of lithic and faunal datasets from both experimental studies and archaeological excavations. The use of experimental approaches is a vital tool for developing criteria to address the identification of projectile technology and associated DIFs and PIMs (Knecht 1997a; Iovita and Sano 2016; Rots 2016). To this end the experiments detailed here provide a first step towards the integration of these datasets and an attempt to illustrate the importance of combining lab-based and more replicative experimental setups.

These experiments have illustrated that PIM formation results from a complex interaction of kinetic energy and how this is dispersed through the target medium. Our results illustrate the problem of equifinality in distinguishing projectile damage from other agents of bone breakage and differentiating between delivery systems. However, the presence of embedded lithics and notched elements with bevelling indicative of directionality offer potential avenues for future research and identification in archaeological assemblages. Similarly, these replicative experiments produced perforation marks on scapulae, which remain, perhaps, one of the clearest signatures of projectile impact (Noe-Nygaard 1973; Roberts 1999; Smith 2003, 2010, Fig. 7.1 p262, 2013).

So, why do we have limited evidence for hunting lesions in the Middle Palaeolithic record? At present, this appears to be a result of limitations in both the methodology and archaeological data. It is possible that it merely reflects a late onset of these types of technology (Gaudzinski-Windheuser 2016) or that Neanderthal populations used a different type of hunting technology (Thieme 1998; Smith 2003; Gaudzinski-Windheuser et al. 2018; Milks et al. 2019). Moreover, it remains a possibility that the often high fragmentation of Middle Palaeolithic faunal assemblages has masked our ability to identify accurately these signatures. However, with the continued development and implementation of controlled and replicative setups, alongside the integration of archaeological lithic and faunal datasets archaeologists should be able to identify DIFs and PIMs in Middle Palaeolithic contexts in the future. An integrative approach utilising lithic and faunal data alongside more standardised methodologies will allow us to more directly address whether the reasons behind the absence of projectile points and associated bone damage is related solely to taphonomic processes or represents a specific behavioural choice by Neanderthal populations.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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