Chapter 2
Identifying Weapon Delivery Systems Using Macrofracture Analysis and Fracture Propagation Velocity: A Controlled Experiment

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Abstract In the last few decades, zooarchaeological studies have demonstrated beyond doubt that the hunting abilities of hominins were quite formidable from quite early on. Unfortunately, direct evidence for the use of weapons in hunting is quite rare and depends heavily on the preservation of organic elements. In particular, in the absence of such evidence, it is notoriously difficult to pinpoint the first appearance of complex, mechanically-assisted projectiles (such as darts and arrows) in the archaeological record. In this chapter, we present data from a controlled ballistic experiment with the aim of establishing patterns in the formation of impact fractures that would allow for the discrimination of thrusting spears, (hand-thrown) javelins, and spearthrower darts and arrows. By controlling for the weapon tip shape, weight, and raw material, impact angle (IA), as well as target composition, we are able to focus on the key elements that separate the different launching systems: velocity and kinetic energy output. The results show that fracture scar length is proportional to kinetic energy at impact, but only if the impact is perpendicular, as acute IAs reduce the energy requirements for the production of large, typical impact fractures. We also confirm previous results of Hutchings (JAS 38:1737–1746, 2011) regarding the relationship between precursory loading rate and fracture propagation speed, documenting a weak linear relationship between the two in our sample. We conclude by discussing the implications of this study for identifying different weapon armatures in the archaeological record.

Keywords Controlled experiments • Weapon delivery mechanisms • Spears • Javelins • Spearthrower darts • Wallner lines • Fracture velocity

Weapon Delivery Systems in an Evolutionary Perspective

Weapons take up a very important role in current portrayals of technological evolution and especially in the discussions about the comparative fitness levels of archaic v. anatomically modern humans (e.g., McBrearty and Brooks 2000). To a great degree, this is because weapons are perhaps the last unchallenged remnant of the image of early hominins as "Man the Hunter" (Lee and DeVore 1968). Nearly all such portrayals focus on the struggle of prehistoric hominins with large, dangerous animals, for which the natural physical disadvantages of the former must have been overcome by the use of increasingly advanced technology. In the absence of such technology, direct close combat scenarios have been inferred, and to a large extent, also documented in the form of trauma patterns on the human skeletal remains. This is especially the case for Neandertals, whose patterns of trauma have been found to match those of rodeo riders (Berger and Trinkaus 1995), although these results no longer seem as strong as they once were (see Trinkaus 2012).

But despite the comical picture of the more ancient hominins battling enormous beasts and getting hurled up in the air by them, recent research in zooarchaeology has shown that the hunting abilities of quite ancient hominins must have been quite formidable (e.g., Farizy et al. 1994; Gaudzinski 1995; Marean and Kim 1998; Gaudzinski and

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Roebroeks 2000; Gaudzinski-Windheuser 2005). Many sites across Europe demonstrate the mass-hunting of bovids, cervids, and equids in the form of monospecific faunal assemblages with good evidence for cut marks (Gaudzinski and Roebroeks 2000; Gaudzinski 2005). Moreover, hominins did not only systematically hunt large and dangerous herd herbivores, but also solitary animals such as rhinoceros (Bratlund 1999). Evidence from several sites in Europe also strongly suggests that Neandertals regularly hunted cave bears, possibly during hibernation (Kindler 2012). Thus, if Neandertals (and possibly earlier *Homo heidelbergensis*) were accomplished hunters, the pressing questions become: what kind of weapons did early hominins use? To what extent can weapon types be correlated with technological and biological evolution?

Almost ubiquitous in the literature is the model of unilinear evolution from thrusting spears to javelins (hand-thrown spears), to mechanically-assisted weaponry, namely spearthrower-propelled darts and bows and arrows (see Fig. 2.1). The latter two are nowadays referred to as "complex projectiles" (Shea and Sisk 2010; Sisk and Shea 2011) and are considered, beyond their improved functionality in terms of impact energy and killing capacity, to also imply complex cognitive processes, both in their production and use (Lombard and Haidle 2012; see also Lombard and Wadley 2016).

We owe this unilinear model in large part to chronological milestones established by extraordinary discoveries of well-preserved organic remains, which allow us to reconstruct, in those specific cases, the whole technology. For instance, the discovery of 300–400 kyr old sharpened wooden implements at Schöningen in Germany [universally interpreted as spears or javelins (Thieme 1997; Rieder 2003)] in association with more than 20 horses seems to provide a baseline for the technology available to the earliest hominins, both in terms of age and quality of the evidence. At the other end, the oldest preserved arrow shafts from Stellmoor, also in Germany (Rust 1943), are only about 10 ka old (Fischer and Tauber 1986; Weber et al. 2011), whereas the oldest spearthrower, from the Solutrean site of Combe Saunière in France, is probably only a few thousand years older, at ca. 18–20 ka (Cattelain 1989; Roque et al. 2001). Between these milestones, there is only indirect evidence of weapon delivery systems, mostly in the form of traces left on stone points, which may point to their use as

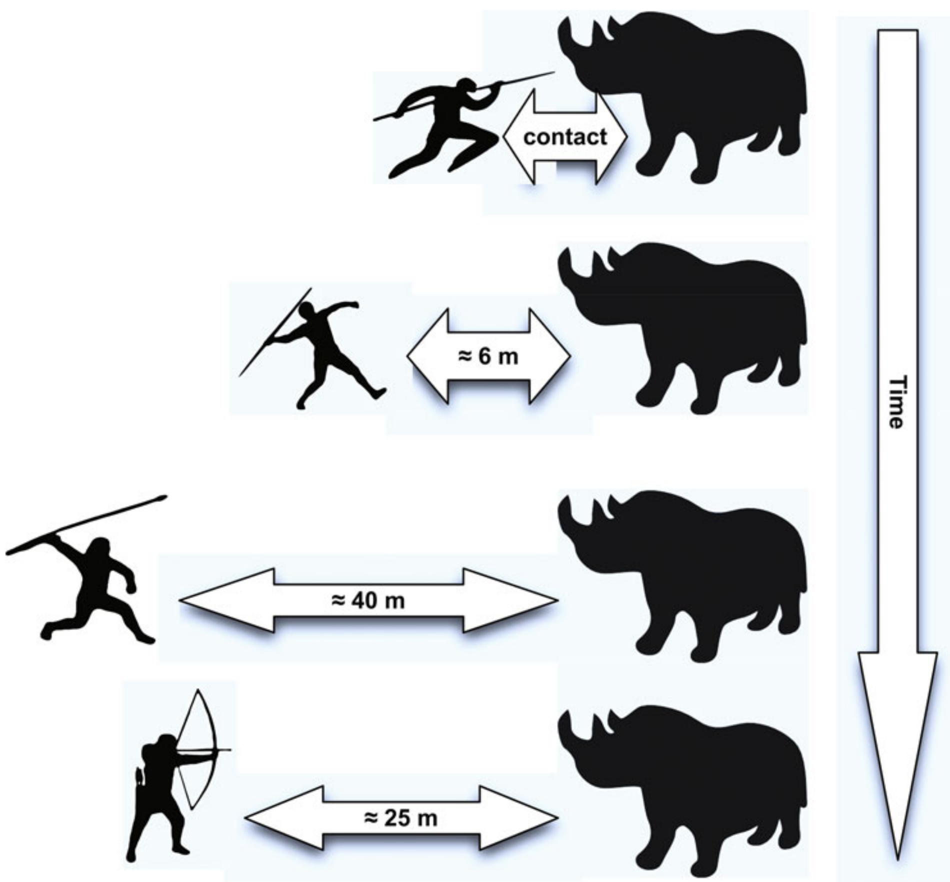

Fig. 2.1 Graphical illustration of the four major weapon delivery types discussed in the literature. Effective distances are from Churchill (Churchill 1993; see also Rhodes and Churchill 2009)

weapon tips. In particular, it seems that we are dependent upon lithic evidence to establish the first appearance of mechanically-aided projectile weaponry, since there are many lithic industries between 300 ka and 20 ka which feature implements that are similar to components of flying projectiles, but no preserved organic parts that could confirm their place within the technology.

The Contribution of Lithic Use Wear Analysis

Especially for the reasons outlined above, the study of impact-related lithic use wear has proven of critical importance. Systematic investigations of macroscopic damage, also known as "diagnostic impact fractures" (DIFs, Lombard 2005) have a long history, with a particularly active period in the 1980s (e.g., Witthoft 1968; Ahler and McMillan 1976; Frison et al. 1976; Barton and Bergman 1982; Huckell 1982; Bergman and Newcomer 1983; Fischer et al. 1984; Odell and Cowan 1986; Geneste and Plisson 1989; Plisson and Beyries 1998). The last decade has seen a renewed interest in experimentation (e.g., Shea et al. 2001; Lombard et al. 2004; Pargeter 2007, 2011; Lombard and Pargeter 2008; Sisk and Shea 2009; Schoville 2010), as well as searching the archaeological record for evidence of different weapon types (Sano 2009; Villa et al. 2009a, b; Lombard 2011; Rots et al. 2011; e.g., Brown et al. 2012; Lazuén 2012; Wilkins et al. 2012). Including the indirect evidence, the picture of unilinear evolution of weapon technologies appears to contain a few surprises. The most recent data from Africa (Wilkins et al. 2012) hints at the appearance of hafted, stone-tipped spears or javelins by about 500 ka, presenting evidence similar to that offered in the 1980s to infer the same function for Levallois points from Neandertal sites (e.g., Shea 1988, but see Plisson and Beyries 1998). Similarly, several recent papers have made arguments in favor of the appearance of bow and arrow technology by 60 (Lombard and Phillipson 2010; Lombard 2011) or even 70 ka (Brown et al. 2012) in South Africa, much before its appearance in Europe, where it is pre-dated by the spearthrower.

However, demonstrating the existence of complex projectiles beyond any doubt requires an extra step beyond demonstrating the existence of weapons per se. In addition to evidence for violent impact, a convincing argument must be made that a launching mechanism, either a spearthrower or a bow, would have been used. Because the latter are almost never preserved, most studies that have tried to identify the launching mechanism so far (e.g., Lombard and Phillipson 2010) have combined the use-wear evidence with metric attributes, which are known to be capable of discriminating between arrow, (spearthrower) dart, and spear tips on a purely metric basis (Shott 1997; Shea 2006). Tip cross sectional area (TCSA) and tip cross sectional perimeter (TSCP), ballistic parameters relevant to a tip's ability to penetrate the target (but see Newman and Moore 2013; Clarkson 2016) have thus been used in conjunction with use wear data to conclude that the studied weapons would have been small and light, and would most likely have been launched with the aid of a propelling device (Sisk and Shea 2011).

Although the combination of multiple lines of evidence may be more or less plausible depending on the case, the only evidence which can establish a weapon tip as having been launched by a mechanical device is evidence of a pattern consistent exclusively with speeds or impact energies beyond what can be achieved with hand delivery (or even through accidents, see also Hutchings 2016). Ideally, we should establish quantifiable, objective criteria for distinguishing between types of weaponry based upon direct consequences of their physical properties. The best approach to understand these sorts of causal relationships is through experiments performed under controlled conditions, where the effect of each relevant variable can be evaluated separately.

Controlled v. Replicative Experiments

In order to infer the existence of any past human behavior from archaeological remains, it is necessary to identify which aspects of that behavior are intrinsically connected with those remains. Because both behaviors and their effects on artifacts are very complex, a simplifying model must be sought in order to focus on the relevant variables and lessen the labor costs of reconstruction. If the behavior is "hunting with penetrative weapons" and the remains are "lithics with use wear", it is necessary to identify which aspects of the former are intrinsically (and causally) related to the latter. Such a project requires a variety of types of experimental work, which are equally important and interdependent. First, as many possible types of hunting must be replicated and the full spectrum of associated lithic use wear catalogued. This first step has been well covered in the past 20 years of experimental research. Second, all identified wear patterns that could be replicated through post-depositional damage or accidents should be eliminated from the catalogue. This type of experiment has come to the foreground in the last few years, especially with respect to the effect of trampling on edge damage (Sano 2009; Schoville 2010; Pargeter 2011). Finally, the types of wear that are expected from theory should be evaluated in controlled and repeatable conditions, in order to focus in on specific physical variables of interest, such as output velocity or kinetic energy.

This last step is crucial to being able to separate wear that is directly caused by violent impact from wear that is caused by ancillary factors. When an experimenter attempts to investigate one variable (e.g., launching system), but in the course of the experiment changes one of the other variables (for instance, tip shape, which is difficult to control through flintknapping), many other variables may be changed as well (such as edge angle, point angle, thickness, etc.), thereby influencing the type and size of the effect (in this case, size, shape, etc. of the damage). It is tempting then to think that the changes in the result are caused by the target variable (in this case, launching system), but the influence of the other unaccounted factors cannot be ruled out, unless they are held constant. In this study, we present two series of experiments aimed at separating thrust spears from flying projectiles, carried out in the most controlled fashion possible, while simultaneously preserving the essential physical properties of the target attributes. More specifically, we control for tip and shaft shape, raw material and weight, while measuring impact velocity and angle.

Materials and Methods

In order to examine the fundamental differences between the damage sustained by points in thrusting v. projectile use, we employed two different series of controlled laboratory experiments. Both series used the same weapon tips and the same target, the differences between them being reduced to the relevant physical quantities related to the load rate and kinetic energies applied to the target at impact.

General Setup

For both experiments we used nearly identical soda-lime glass copies of a Levallois point from Jabrud, Syria (Rust collections, University of Cologne, original dimensions (mm): 64.5 (length), 36.5 (max. width), 6 (max. thickness) (see Fig. 2.2). The copies were cast in soda-lime glass, a standard material science experimental substance with known brittle fracture properties, using a waffle-iron-like metal form. Glass is a good substitute for other siliceous rocks, including obsidian, that might have been used by prehistoric people to make projectile points, mainly because it breaks in the same way. Naturally, due to differences in the formation processes of flints or silcretes, these rocks will probably exhibit some differences from glass, whereas obsidian, which is volcanic glass, will be most similar. However, carrying out the tests with any one of these rock types would produce results that are different from the

Fig. 2.2 Six hafted copies of the Jabrud Levallois point, including the foreshafts

others, and glass presents the advantage of being easily shaped through heating. The shape of the cast points is identical visually, but the points needed to be filed on the ventral side in order to avoid having jagged irregularities, due to the accumulation of glass droplets when the form was closed. Filing the points adds to the convexity of their ventral side, departing from the typical Levallois point shape. In order to check the variability of the glass-casted copies, the same simple measurements were collected on a random sample of 53 points, and the following coefficients of variation (CVs) were obtained: 0.009 (length), 0.026 (max. width), and 0.041 (max. thickness), and 0.035 (weight). The CV values are extremely small, suggesting that the points can be treated as essentially the same, at least with respect to their ballistic properties.

Both series of experiments likewise used the same target, which was fastened onto a 22 kg steel box (see Fig. 2.3), featuring an inner compartment which pivots around an axle at the bottom, allowing the control of the AI in 15-degree intervals, from 90° to 30°. A further slot for a 20° angle was never used in the experiments, because the spear frequently hit the upper part of the tilted steel frame by accident. The inner compartment is further divided in two sections, both filled with 20% ballistic gelatin, and separated by interchangeable plates of bone-like polyurethane. The synthetic bone plates, manufactured by SynBone AG, are 6 mm thick, and are specially designed to be used in ballistic testing. They mimic the structure of mammalian bone (including cortical and trabecular bone) and are covered in a thin layer of rubber, which is similar to the periosteum. Originally held in place by a steel slot, the bone plate was eventually sandwiched between a 2.5 cm thick slab of gelatin on the impact side and an 8.5 cm thick block on the other side. This was done so as to mimic the position of a bone within

Fig. 2.3 View from above of the target with the spear having exited at the back. Note the four layers, from left to right: Leather, gelatin, polyurethane "bone" plate, gelatin

muscle and other soft tissue more realistically, allowing for elastic absorption of the impact. Finally, ≈2 mm-thick scraps of cow leather were pressed against the outer gelatin, completing the target.

Likewise, in both experiments, the points were slot-hafted in machined pine wood foreshafts, which were then screwed onto metal spear shafts. We used natural beeswax as an adhesive. Beeswax is known from ethnographic as well as Paleolithic archaeological contexts (d'Errico et al. 2012) and presents the advantage of a quick and strong bind. However, it is equally easy to remove the points by simply heating the foreshaft, allowing for a time-efficient firing of more specimens.

Projectile Experiment

The first experiment (described in greater detail in Iovita et al. 2014) focused on isolating the two major causes of damage production, namely projectile impact velocity and angle (IA) from other situationally variable factors that can influence these patterns in a real-life hunting episode. In this series, the foreshafts containing the hafted points (n = 234) were attached to an aluminium tube (total weight of the spear ≈266 g) and propelled by an air-gun into the target from close range (free flight 24 cm). The launching mechanism does not allow for the spinning of the spears, so that the target is always hit identically. This does differ from a variety of hand-thrown motions, but was chosen for reducing complexity in the number of variables. The air gun chamber is capable of pressures between 1.25 and 15 bar, resulting in projectile speeds (for the 266 g spear) between ca. 7 and 30 m/s. The velocities were measured by a transient recorder connected to a set of light curtains (see Fig. 2.4).

The largest final velocity produced by our air gun (≈30 m/s, 110 km/h) corresponds to some atlatl-delivered darts (Raymond 1986; Stodiek 1993; Hughes 1998; Baugh 2003). Stodiek's high-speed camera (1993:194) recorded an approximately 70 km/h (≈20 m/s) final velocity at entry into the target at 25 m distance – but with a spear that weighed only 90 g. This corresponds to ≈19 J of kinetic energy, much lower than our highest values of over 100 J. Hutchings and Brüchert (1997) obtained much higher velocities than any other study, and for their dart (of similar weight, 273.4 g),

Fig. 2.4 Air gun for the projectile experiments. A detailed description, including all measurements can be found in Iovita et al. (2014)

they report initial velocities in the range of 34.9–64 m/s, with an average value of 42.5 m/s. Using their estimate of velocity loss of approximately 10% over the effective distance of 15 m to the target, and taking into account that our experiment measured essentially impact velocities, our highest values overlap with the lower range obtained by that study. Based on previous published results, we consider our range to be relatively comprehensive in terms of velocities and kinetic energies at impact, ranging between hand-thrown and atlatl-delivered flying projectiles (Fig. 2.4).

Thrusting Experiment

Since thrusting can deliver similarly high energies to those obtained by high-speed launching projectiles, but at considerably smaller speeds, the type of applied load is quite different. This has been previously mentioned in the literature (e.g., Shea et al. 2001; Hutchings 2011). With the exception of one experiment aimed at investigating the effect of thrusting and throwing loads on the bone morphology of the human shoulder (Schmitt et al. 2003), most experiments aimed at replicating thrusting did not measure the speed of the thrusting motion and did not calculate the associated kinetic energy of the spear. Shea et al. (2001:810) cite measured results out of the forensic literature on knife stabbing (e.g., Chadwick et al. 1999; Horsfall et al. 1999), putting the speed of the spear itself between 1 and 1.5 m/s, and the resulting energies at about 28–63 J. The speeds used in our experiment are in a similar range, from 1.1 to 2.7 m/s. However, in two-handed spear thrusting, at least a portion of the attacker's own weight is added to the spear in an attempt to increase momentum. In our second experimental series, we tried to approximate this in a controlled fashion, by implementing a system of weights that would guarantee a sustained force exerted on the target both during and shortly after the impact (see Fig. 2.5 below).

In our setup, the same Levallois points (n = 43) were hafted to their foreshafts and screwed into a metal bar, which was suspended from the ceiling at both ends, making a pendulum with 2 fixed points. 10, 20, 30, and 60 kg weights were successively added to the bar in a symmetrical fashion and the spear was launched from a variety of distances (30, 50, and 70 cm from the target). The impact velocities were measured using the same light curtain and transient recorder system used for the projectile experiments, making use of an attached metal bar hanging from the underside of the main spear shaft. The impact angle (IA) was always 90° in this experimental series. In case the spear bounced back from the target, it was caught by one of the experimenters in order to avoid double hits.

Macrofracture Analysis

Following the launch, each point was removed from the haft and the fracture type was recorded, along with the scar length and the missing length and placed in a labelled plastic bag. The fractures were identified and photographed with the aid of a Leica M420 macroscope, with magnifications up to 40x. The fracture typology followed those used by the major experiments in the 1980s, e.g., Barton and Bergman (1982), Fischer et al. (1984), and Odell and Cowan (1986), also reviewed more recently by Dockall (1997), and Sano (2009; Iovita et al. 2014). We use six major categories of damage:

1. flute-like (subsumed under longitudinal)
2. burin-like (subsumed under longitudinal)
3. transverse/snap
4. spin-off (secondary fracture)
5. tip crushing
6. microscopic (incipient or very small fractures)

In each case, only the largest fracture was used for the classification, although the presence of multiple fractures was noted. Because it was not always possible to refit the missing flakes back on to the tip, multiple fractures were only noted where they were believed to have hit the plate several times, which was corroborated with skipping marks on the plate. Finally, for each fracture, the type of initiation and termination was recorded according to the Ho Ho Committee (Cotterell et al. 1979) definitions.

Fracture Propagation Velocity

A positive relationship between the loading rate and the resulting crack or fracture propagation velocity was implied by the Griffith fracture concept (Griffith 1921) and later demonstrated experimentally (Richter 1974; Kerkhof 1975). The first attempts in archaeology to infer impact loading rate from measurements of crack velocity were made in the 1980s by Tomenchuk (1985), who first tried to use this method to distinguish between pressure and percussion flakes. He calculated crack velocity from visible secondary fracture characteristics, such as Wallner Lines (Wallner 1939) and fracture wings (*Bruchschwingen*) according to the methodology prescribed by Kerkhof and Müller-Beck (1969), Kerkhof (1975). This methodology was extended by Hutchings, who used it to demonstrate pressure flaking for some Clovis flutes (Hutchings 1999), and, more recently, for quantifying the difference between different weapon launching systems (Hutchings 2011; Sahle et al. 2013). These publications contain very detailed accounts of the procedure for identifying and calculating instantaneous fracture propagation

Fig. 2.5 Thrusting pendulum, in this photo loaded with six 10 kg weights

velocity, and so a review of these protocols will not be repeated here. In practice, this velocity can be calculated trigonometrically, by measuring several angles related to the intersection of a Wallner Line and the direction of the crack front or another Wallner Line. The geometry of the intersection is determined by the ratio of the transverse wave speed (c_2) and the crack front velocity (or fracture propagation velocity, $\dot{c}$), and since the former is a constant for each material, the velocity of the crack front at the point of intersection is a function of the intersection's geometry.

The pieces were taken out of their bags by a student and re-labeled with different codes, so as to avoid confirmation bias. The correspondence to the original experiment numbers was noted on a separate piece of paper to be checked at the end of the measurement series. One of us (RI) then photographed the pieces through an adapter to the microscope and performed the measurements on them using ImageJ (Fiji). Whenever possible (i.e., whenever multiple Wallner lines were visible), multiple measurements along the fracture surface were taken between 20 and 50% of the fracture length, and the maximum measurement was repeated three times. Unfortunately, this was only possible in a few cases, the majority of fractures exhibiting only one feature suitable for measurement. The measurements were repeated three times using the same point (recorded on a saved copy of the original image) at one week intervals, so as to avoid repetition bias.

Results

Macrofracture Patterns

Essentially, the results from the thrusting experiments can be differentiated from the ones of the projectile experiments by a much higher proportion of tips that were actually damaged. As can be seen in Fig. 2.6, the proportions of longitudinal macrofractures in the two samples (61:147 and 23:19, for projectiles and thrust spears respectively) are markedly different and the difference is statistically significant (Chi-squared = 9.03, df = 1, $p < 0.01$). This makes sense from a ballistic point of view. Given a similar amount of kinetic energy, the slower impact will be less likely to break the target, and the point will be more likely to suffer damage itself.

This can also be seen in the comparison between the proportions of the different fracture types in the thrust spears and the three sets of 10 identical shots at low (≈9.5 m/s), middle (≈15.5 m/s) and high (≈30 m/s) speeds (see Fig. 2.7, see also Iovita et al. 2014).

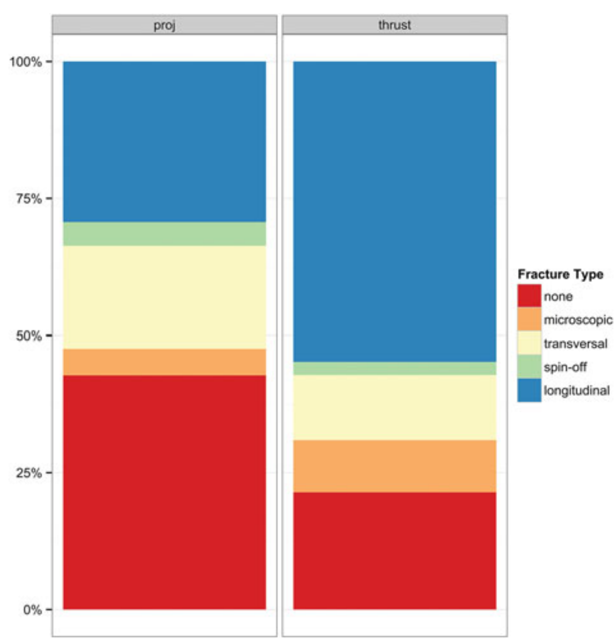

Fig. 2.6 Main differences in the types of fractures obtained in the two experiments

In terms of the scar lengths, there are no significant differences between thrusting and projected points of similar energies (see Fig. 2.8). The projectiles in the fastest quarter of the speed range obtained significantly larger damage scars than any of the thrusting spears, confirming the expectation that kinetic energy determines the size of the flake(s) removed at impact.

However, when the data are analyzed in raw form, there appears to be no relationship between kinetic energy and scar length, unless the impact angle (IA) is kept constant at 90°. In the latter case, the relationship is linear and the regression is significant ($t = 3.13$, $p < 0.01$ for projectiles, $t = 2.07$ and $p < 0.05$ for thrust spears) but weak for both projectiles and thrust spears ($R^2 = 0.4$ for projectiles, but only 0.1 for thrust spears; see also Fig. 2.9).

Fracture Propagation Velocity Results

Although secondary fracture features such as Wallner Lines and fracture wings are difficult to see on reflecting materials such as glass, it was nevertheless possible, through the use of a light diffuser and by focusing the objective to slightly below the surface (where Wallner Lines actually form), it was possible to obtain photographs on which measurements were possible (see Fig. 2.10) on a total of 48 pieces ($n_{thrust} = 15$, $n_{proj} = 33$). Since all the specimens presented here are made from the same soda-lime glass, and in order to allow an easier comparison with other raw materials from other experiments, the values reported are in terms of the ratio between the fracture propagation velocity ($\dot{c}$) and the transverse wave velocity (c_2), rather than in m/s.

Hutchings (2011, Table 3, see also Fig. 8) proposes the use of three loading rate ranges, corresponding roughly to $\dot{c}/c_2$ ratios between 0 and 0.10 (quasi-static), 0.10 and 0.38 (rapid), and above 0.38 (dynamic). In Hutchings's experiments, values of up to 0.58 of the transverse wave speed were calculated for both dart and arrow armature impacts.

In our experiments, we were largely able to confirm Hutchings's results, as can be seen from Fig. 2.11. The relationship between weapon velocity and fracture velocity expressed as the $\dot{c}/c_2$ ratio is linear and the regression of weapon velocity on the $\dot{c}/c_2$ ratio is significant, although the relationship is noisy ($R^2 = 0.34$, $p < 0.01$).

If we restrict the analyses to the range of kinetic energies common to both flying projectiles and thrust spears (in this experiment 6.4–58.2 J), there is no relationship between fracture velocity and kinetic energy, further confirming that the method is not sensitive to the amount of energy, but rather the precursory loading rate. We were unfortunately not able to statistically test the effect of angles on the $\dot{c}/c_2$ values obtained, because of too small samples of readable

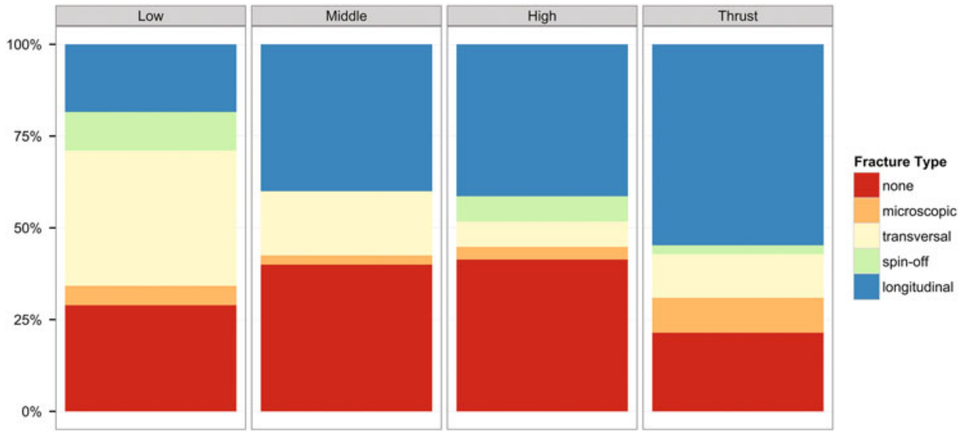

Fig. 2.7 Comparison of the types of fractures by controlled speed interval at IA = 90° (see text for the velocities for each trial)

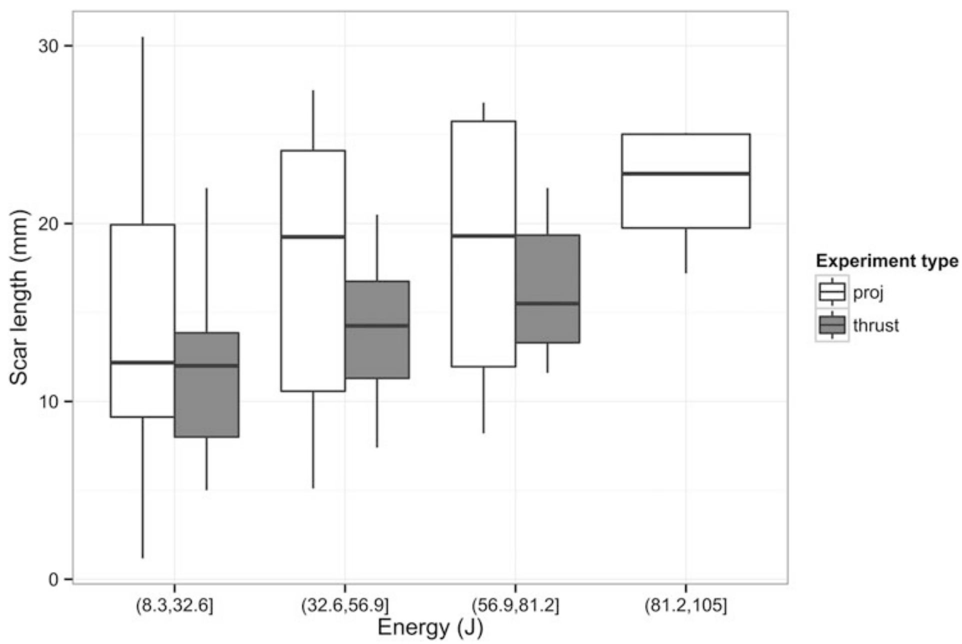

Fig. 2.8 Graph of scar length against the four equal intervals of kinetic energy. None of the thrust spears produced energies in the highest interval

secondary fracture characteristics per angle category. However, as recent results show (Iovita et al. 2014), acute impact angles significantly improve the chance of a fracture developing at any given speed and also influence the size of the resulting fracture, so the effect of the impact angle should be further investigated in the future.

Despite the many commonalities, there are also some differences from Hutchings's results that we wish to discuss. First, although our range for our thrusting spears, 0.07–0.22, is almost identical to that of Hutchings (2011, Table 3, 0.02–0.21), our median was 0.15, well within his "rapid" range. In that study, 84% of the fractures on spears remained in the "quasi-static" range with values not exceeding 0.10. It is possible that we used slightly higher velocities for our thrust spears, but it is difficult to compare our results directly with those of hand-thrust spears. Second, we did not obtain even a single fracture speed beyond 0.38, that is, within the "dynamic range". The obvious explanation for this is that the speeds we used are within the lower part of the range of darts and arrows used by Hutchings (2011) and derived from his earlier performance experiments with spearthrowers (Hutchings and Brüchert 1997). In the latter experiments, initial velocities in average of ≈42 m/s for a dart of similar weight were recorded, estimating ≈38 m/s at target entry. Due to the limitations of our machine, we could not accelerate our spear to more than 30 m/s. However, given that the bone plates would almost

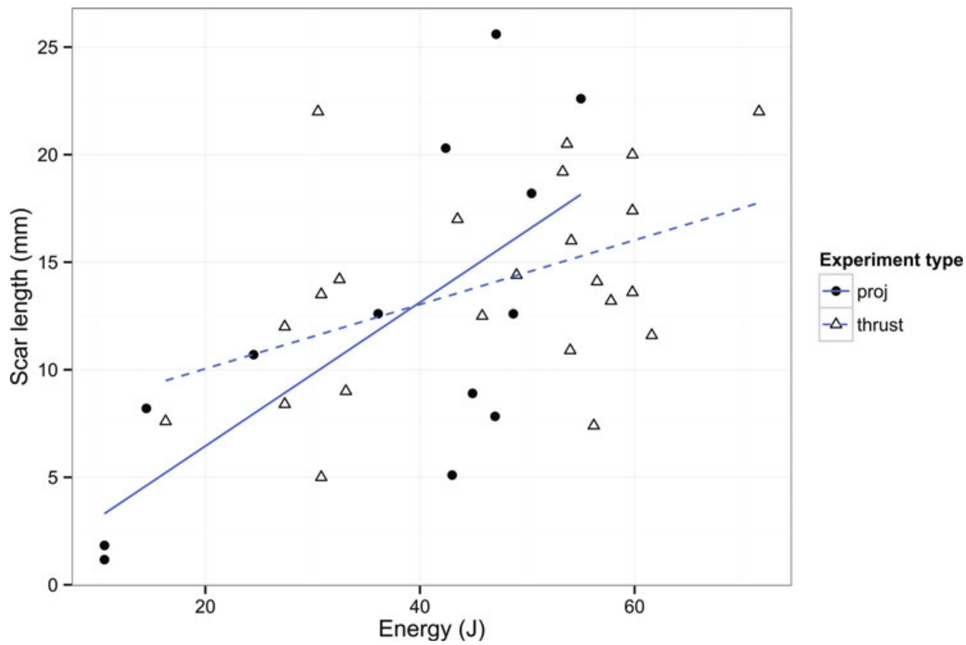

Fig. 2.9 Plot of kinetic energy against scar length, showing a weak, but significant linear relationship for both thrust and flying weapons (IA = 90°). Only points with longitudinal macrofractures were counted, as it is difficult to measure other types of breaks accurately

always break upon impact at this velocity, leaving the points undamaged, we did not pursue the objective of increasing launching speed any further. All other experiments with spearthrowers recorded launching speeds well below those of Hutchings and Brüchert (1997) and it is likely that different constructions would have resulted in different weapon launching power. For example, it is a well-known fact that many of the bows of modern hunter-gatherers are quite small and weak, such as those of the San bushmen, which often cannot draw more than 8–10 kg (Bartram 1997). Therefore, it is probable that the velocities obtained by Hutchings and Brüchert (1997), and hence, the fracture velocities from the later experiments (Hutchings 2011) represent an upper limit for what one might encounter archaeologically in the early development stages of complex projectile technology.

Discussion and Conclusions

As the present experiments show, simple macrofracture analysis does not help to distinguish thrusting from projectile impacts. If even controlled experiments where points are shot only once in standardized targets do not provide sufficiently nuanced patterns for the detection of different projectile weapon speeds, it is difficult to imagine that one could succeed after the reintroduction of all the ancillary factors likely to occur in realistic hunting scenarios. As we have shown quantitatively and with a large sample, the main difference between thrust spears and flying projectiles seems to be that thrust spears suffer more damage to the points than flying projectiles of similar kinetic energies. This result confirms previous observations (e.g., Lombard et al. 2004) and makes sense ballistically, since spear thrusting is very slow, even compared with simple projectiles. For comparable kinetic energies, at slow speeds and high momentum, the weapon tip penetrates the bone plate more frequently, but without shattering it. The result is often point failure through shearing after continuing to be pushed forward. In contrast, with high-speed impacts, the bone plate often shatters instantly, leaving the point intact.

In an archaeological setting, however, this difference is unlikely to survive, due to the likely repeated use, as well as curation and recycling of undamaged points, which would make it difficult to distinguish weapon technologies based on frequency of damage. However, one possible implication of the higher number of damaged points for thrusting spears is an expectation of a higher number of bones in faunal assemblages exhibiting embedded spear tips. However, the only type of damage on bone that is possibly diagnostic for projectile use is the perforated scapula (Smith 2003). Unfortunately, such evidence is extremely rare, and becomes common in periods where complex projectiles are already known (e.g., Bratlund 1991, see also Gaudzinski-Windheuser 2016). Other studies (Rots et al. 2011) have identified gestures that may be associated with spear thrusting, such as a twisting motion, aiming either to cause more internal damage, or to facilitate pulling the spear out. This would result in the co-occurrence

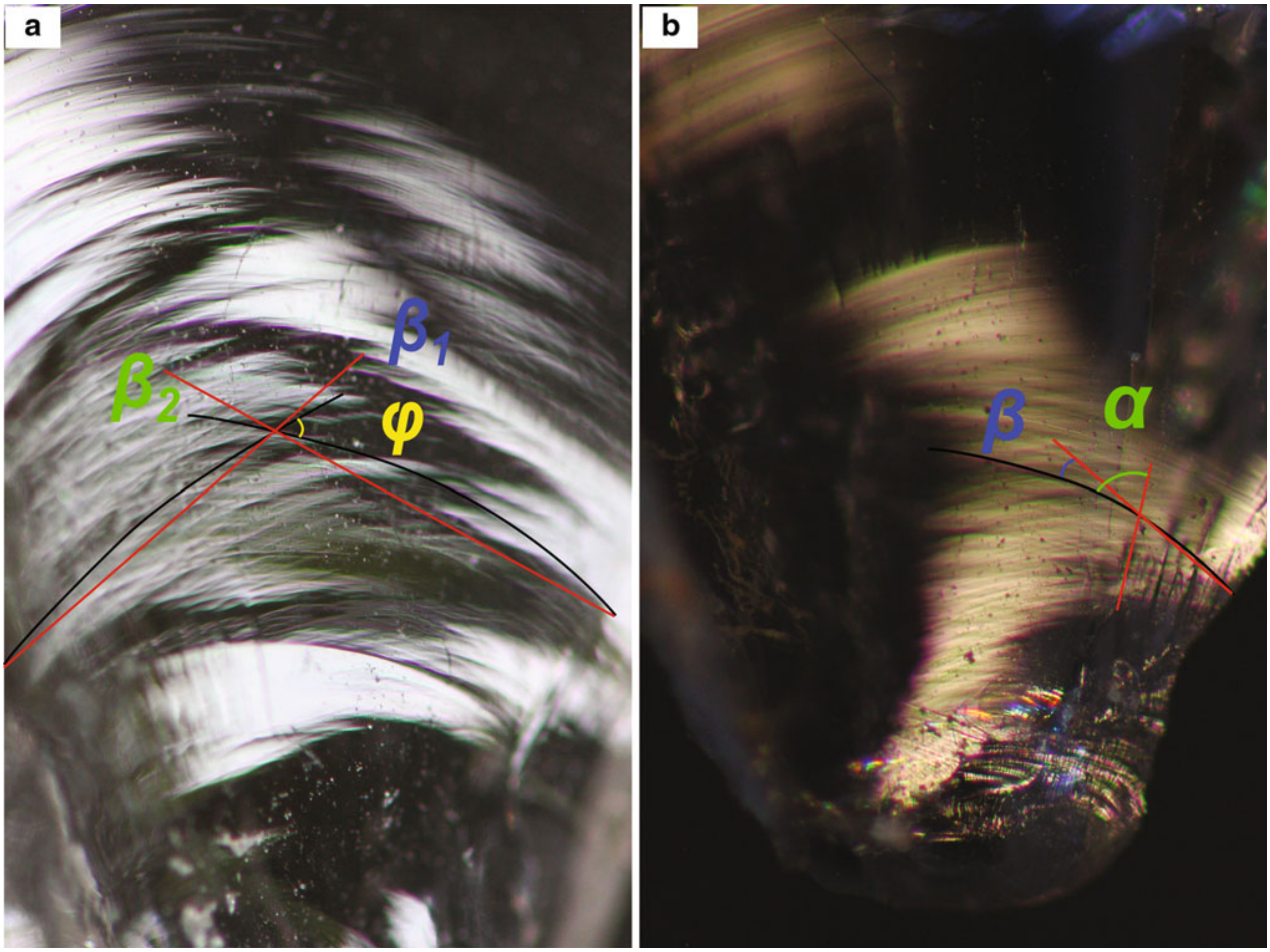

Fig. 2.10 Two fractures exhibiting clear crossing sets of Wallner-Lines. **a** v = 21.5 m/s, $\frac{c'}{c_2} = \frac{sin(\varphi)}{\sqrt{cos^2(\beta_1) + cos^2(\beta_2) + 2cos(\beta_1)cos(\beta_2)cos(\varphi)}} = 0.34$; and **b** $v = 13.6\,\mathrm{m/s}$, $\frac{c'}{c_2} = \frac{cos(\alpha)}{cos(\beta)} = 0.27$

of an impact and a torsion fracture, but this has not been so far researched in a systematic fashion, and unfortunately, twisting motions in and of themselves could be the result of other tasks than spear thrusting.

The so far best method for identifying weapon technology based on use wear is through the calculation of fracture propagation velocities using one of Kerkhof's (1975) protocols, also outlined in Hutchings (2011). We were able to confirm that a linear relationship between projectile speed and fracture speed does exist and is independent of the kinetic energy output. However, the relationship is relatively weak ($R^2 = 0.34$), with a large variation of fracture velocities observed for any particular projectile speed, something also mentioned by Hutchings (2011). This means that, given a sufficiently large sample representing only one, or two very different weapon launching technologies (one slow, one very fast), one could determine roughly in which range of speed the respective weapons might have been used. However, this picture is complicated by the fact that the rapid range, where the majority of the fracture speeds in this experiment fell, contains many fractures that have nothing to do with weapon use, such as flintknapping and dropping accidents, and possible other intentional tasks that involve impacts.

Moreover, projectile speeds of up to 30 m/s, common to many complex projectiles, could also exhibit fracture speeds that only span the rapid range, meaning that this method is only useful for the identification of extremely fast complex projectiles. While it has been demonstrated that atlatls can

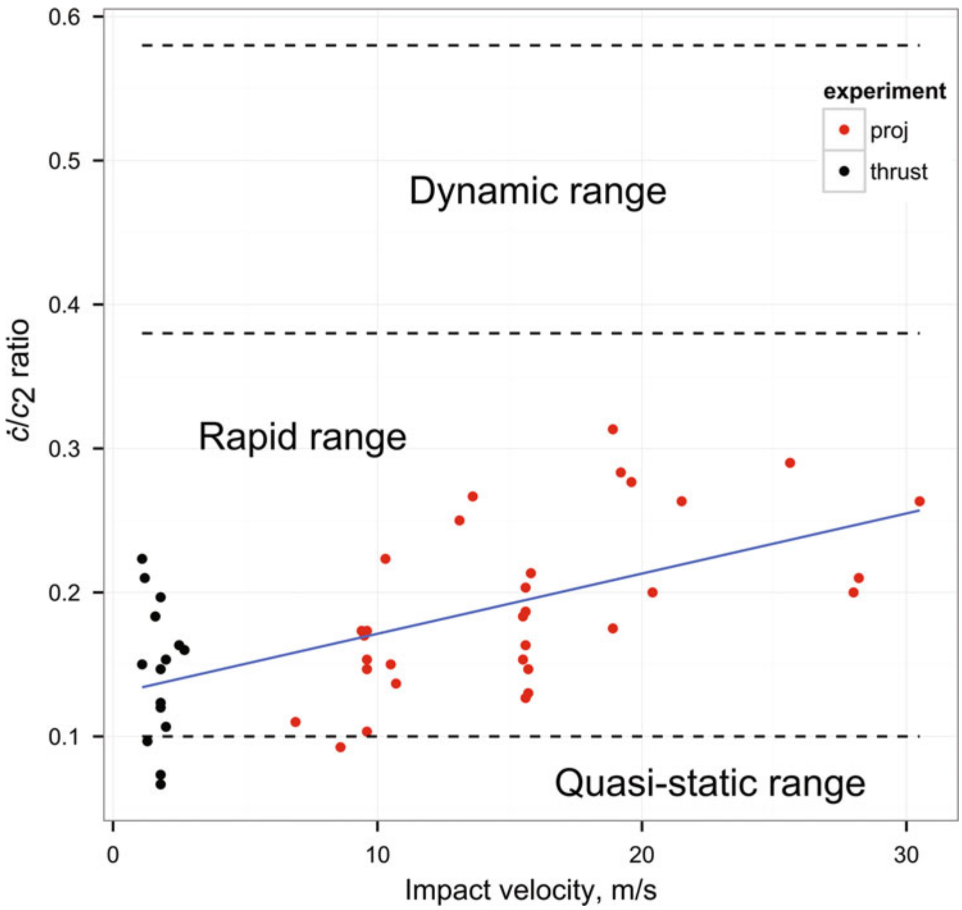

Fig. 2.11 Graph of weapon impact velocity against fracture propagation velocity, expressed as the $\dot{c}/c_2$ ratio. Note the lack of points in the dynamic range

accelerate darts up to 64 m/s (Hutchings and Brüchert 1997), more studies of different constructions are needed to assess how typical such speeds might have been in the past.

Similarly, fracture propagation velocities are useful for identifying thrusting spears, if very low fracture speeds ($\dot{c}/c_2$ ratio below 0.10) are observed. However, if fractures only spanning the rapid range are observed in an assemblage, it will be impossible to distinguish between any of the three major types of launching system, unless the fractures are associated with other attributes (such as standardized shape) that can be used as independent clues.

In conclusion, we must remember that hunter-gatherers often use a mixture of weapons, depending on the type of game and hunting situation (e.g., Churchill 1993). Tool recycling and site function are expected to play an important role in determining the frequency of usable data for answering questions about the type of launching system, especially if weapon tips are made of a single piece (as is the case for many tanged arrowheads or bifacial points), being more likely to change function following incurring too much damage. In any case where a complex projectile technology is suspected, a thorough study of the fracture velocities should be carried out. Such a study may reveal a few specimens that can be placed in the dynamic range, demonstrating beyond doubt that this is the case; however, a negative result does not rule such a technology out and for such cases only a suite of converging lines of evidence can provide a convincing argument in favor of complex projectile technology.

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