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Projectile impact fractures and launching mechanisms: results of a controlled ballistic experiment using replica Levallois points

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ABSTRACT

Identifying the use of stone-tipped projectile weapons in prehistory is important for understanding hominin strategic behavior and cognitive capacities. Such identifications are based on 'diagnostic impact fractures' (DIFs), assumed to form as a result of collisions between the tips and organic materials in the prey body. However, demonstrating weapon use requires documenting an impact speed and/or kinetic energy beyond those likely to occur accidentally or as a by-product of other tasks. We present a new experiment aimed at investigating the influence of speed on impact fracture formation in controlled conditions. Using an air-gun, we fired 234 nearly identical spears tipped with copies of a Levallois point cast in soda-lime glass into a composite target made of polyurethane bone-like plates, ballistic gelatin, and leather. The impact speed ranged from ≈ 7 to ≈ 30 m/s and the impact angle (IA) varied in increments of 15°, from 90° to −45°. We show that realistic DIFs can be produced under these controlled conditions. The frequency of longitudinal tip macrofractures is directly proportional to the impact speed but inversely proportional to the IA. The relationship between the tip fracture type and the type of damage left on the target explains the contact conditions for the formation of different DIFs. No relationship between either initiation or termination type and speed could be established. Therefore, we conclude that 'step-terminating bending fractures' should not be considered diagnostic of weapon use without further supporting evidence. Further, although fracture length increases with speed when IA is held constant, a great deal of overlap exists between trials with different IAs. Given the expected high variance in IA in real hunting situations, large longitudinal macrofractures on the tips of archaeologically recovered lithics should not automatically be interpreted as resulting from the use of high-speed projectiles. We discuss the study's implications for the differentiation of prehistoric weapon-delivery systems, especially regarding recognizing stonetipped weapon use by Neandertals.

1. Introduction: fractures diagnostic of impact and impacts diagnostic of weapon use

Reconstructing Paleolithic weapon technologies is important for understanding not only past hunting strategies, but also for assessing the technical competence, and, consequently, intelligence and cognitive capacities of prehistoric hominins (Lombard and Haidle, 2012; Lombard and Phillipson, 2010; Wadley, 2010). We know from the zooarchaeological evidence that hominins were capable of successfully hunting and even focused on large animals from quite early on (e.g., Farizy et al., 1994; Gaudzinski, 1995; Gaudzinski and Roebroeks, 2000; Gaudzinski-Windheuser, 2005; Marean and Kim, 1998; Villa and Lenoir, 2009). However, unraveling the nature of the technologies used for hunting remains dependent upon researchers being able to identify weapons in the archaeological record. Because traces left behind by weapons on animal bones are quite rarely preserved and because of the comparative lack of experimental studies on this topic (but see Castel, 2008; Letourneux and Pétillon, 2008), the identification of weapon use is usually made from wear traces on the putative weapons themselves.

In particular for stone-tipped weapons, macro-traces that are usually interpreted as indicating penetrative weapon use (and especially the use of flying projectiles) are called 'diagnostic impact fractures' (DIFs sensu Lombard, 2005). The term 'diagnostic' is only appropriately applied to damage which could not have been produced by other tasks such as boring/piercing, cutting, chopping, etc on the one hand, and also not from accidents or taphonomic factors

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on the other hand. For that reason, establishing a set of DIFs is a two-part project:

1) establish a broad set of fractures (and other wear traces) that can occur in hunting contexts (see Dockall, 1997 for a comprehensive review); and
2) perform taphonomic and other studies of equifinality, trying to establish if the relevant fractures from 1) can be obtained through means other than hunting impacts and thus eliminated from the 'diagnostic' category.

Several studies in the second category have concerned themselves with the effect of post-depositional processes (e.g., trampling, see Pargeter, 2011; Sano, 2009; Schoville, 2010) on the presence and distribution of DIFs on archaeological material. However, one aspect that has received less attention and which must not be forgotten is that even fractures definitely resulting from impacts do not necessarily imply weapon use, since accidents during flintknapping and from dropping involve genuine impacts and could produce similar fractures (Hutchings, 2011).

Distinguishing accidental or ambiguous impacts from real weapon use is a question of identifying the kinetic energy of the impact and being able to single it out as sufficiently large to warrant the interpretation of intentionality. Furthermore, recognizing different flying projectile weapon types, such as javelins (hand-thrown spears), spearthrower-darts, and arrows is likewise dependent upon establishing a clear relationship between energy output of the weapon and the qualitative and metric attributes of the damage incurred. The importance that the invention of 'complex,' i.e., mechanically assisted (sensu Shea and Sisk, 2010) projectile weaponry bears for human evolution is such that developing new criteria for distinguishing between the three major launching types should be a top priority for archaeologists working in the Paleolithic. For this purpose, a precise understanding of how kinetic energy, and, as we will see below, especially speed influences the formation of tip fractures during the use of Stone Age penetrative weapons is absolutely crucial.

A quick survey of the literature on experiments with lithic weapons shows that much effort has already been expended exploring the possible wear patterns incurred by weapon tips, as well as possible effects of taphonomic disturbance. The influence of the kinetic energy output of the weapon system has, however, not been studied in a systematic and reproducible fashion. Thus, although we do possess a large library of possible fracture patterns, we do not know how they are related to the variables that are most relevant to reconstructing intentionality: impact speed and kinetic energy. As Lombard and Pargeter (2008:2526) note:

Many other researchers have conducted hunting experiments with stone tools and have discussed resulting fractures (see Dockall, 1997 and references therein), and although terminology frequently differs, it seems that the formation of the fracture types is similar regardless of the type of hunting experiment (Dockall, 1997: 321), tool morphology (Fischer et al., 1984), or raw materials (Lombard et al., 2004).

That the same kinds of fractures keep reoccurring despite varying major variables is encouraging regarding the strength of the signal for impact, but suggests at the same time that too many variables may be affecting our ability to focus on teasing apart the essential functional attributes. We argue here that any attempt to document a relationship between the frequency of type and size of damage and the energy output of the launching system requires the standardization and control of all other variables, i.e., tool morphology and raw material, as well as target attributes. Controlling these variables allows us to focus on the effect of the crucial ballistic parameters. For example, based on the results from controlled impact experiments in fracture mechanics (e.g., Dibble and Whittaker, 1981; Tsai and Kolsky, 1967), the kinetic energy (KE) at impact should determine the size of the fracture, all else being equal. A certain value of kinetic energy can be achieved in practical use with different combinations of delivery speed and projectile mass. Because the kinetic energy increases with the square of the velocity, but only linearly with mass, equal changes in the velocity will influence KE more than changes in the mass, and hence, having tight controls on both variables is very important for such experiments.

To a certain extent, efforts in this direction have already been taken, although we are not aware of any completely standardized studies to date. Following Shea et al. (2001), an increasing number of experimental studies have used calibrated bows or crossbows to control for the initial speed of the projectiles (Churchill et al., 2009; Hutchings, 2011; Lombard and Pargeter, 2008; Pargeter, 2007; Schoville, 2010; Waguespack et al., 2009). In terms of variable control, this is a massive improvement on the hand-held bows and thrown spears of experiments in the 1980s, but the different distances between launcher and target in different studies render the calculation and comparison of impact (final) velocities and kinetic energies difficult.

Another important source of variability in replicative or 'realistic' experiments has been the difference in shape among weapon tips and shafts, as well as the difference in targets used. The first is a natural consequence of using realistic stone-tools, knapped by the experimenters themselves, and which can never be identical to each other. To a certain extent, this is avoided in experiments that use composite tips made with geometric microliths (e.g., Lombard and Pargeter, 2008; Lombard and Phillipson, 2010; Pétillon et al., 2011; Schoville, 2010; Yaroshevich et al., 2010), because the latter are easier to manufacture in a standardized fashion. However, many stone tool industries, including all those produced by Neandertals, do not feature microliths at all, and therefore a different method is required for inference about possible weapon tips based on unretouched flakes.

An additional problem is that of target heterogeneity. This is mostly due to the use of animal carcasses, or parts thereof, all of which differ in their physical properties. Combined with the already discussed uncertainty about the impact speed, target heterogeneity results in a drastic reduction of sample sizes in most experiments. Moreover, almost all published experiments featured the repetition of shots until damage was visible. This means that it was possible to hit bone on one try and flesh on a different try, and that an incipient, microscopic fracture could develop on a subsequent try. While this is how prehistoric people would have used weapons, and although conveying important information about attrition, repeating shots makes it difficult to pinpoint the causal relationship between delivery speed and fracture type and size. Moreover, because of understandable research costs, animal targets are reused during the course of an experiment, meaning that shots later in the sequence have higher chances of hitting rock and bone debris from previous shots, further influencing the outcome of the experiments. The compounding of the above-mentioned factors amounts to a degree of equifinality of wear traces on projectile tips which justifies any attempt to separate them out. As such, the standardization of targets, as well as the use of mechanical aids have been previously signaled as important areas of improvement by other workers (Sisk and Shea, 2009).

In this article we describe a new experimental design developed to improve our ability to explain the observed damage patterns as a function of the variables relevant to distinguishing between different weapons technologies, namely the kinetic energy output and speed of the projectile.

2. Materials and methods

2.1. General setup

Our experimental setup (see Fig. 2) is designed to eliminate all situational aspects of projectile use, that is, all aspects that have less to do with the technology itself and more to do with the setting of the action, which would likely have varied strongly from case to case in real-world situations. The intention is to investigate the role that the key elements of projectile delivery systems, namely the speed and associated kinetic energy generated by the launching system, play in the formation of different types of fractures on projectile tips. In addition to speed and kinetic energy, the impact angle (IA), although a situational variable (and considered a major confounding factor by Odell (1981)), was taken as a major focus of investigation because oblique angles are known to play an important role in the formation of flakes in flintknapping experiments (e.g., Dibble and Rezek, 2009; Speth, 1975). In order to isolate and vary speed and angle independently from each other, we had to homogenize projectile tip and shaft variables, as well as the consistency of target materials. Each tip was shot only once, then removed and put away for analysis. Although this meant that many projectile tips remained unbroken, our goal was not to analyze durability, since both the target and the point are artificial. Instead, we focused on the types of fracture produced by single impacts. In real-life situations, it is possible to envision that single-impact fractures differ from fractures developed through repeated shooting. In such cases, future experiments can be designed to compare the two.

2.2. Projectile tips

A plastic copy of a Levallois point from the Middle Paleolithic site of Jabrud (Syria), located in the University of Cologne collections (original dimensions (mm): 64.5 (length), 36.5 (max. width), 6 (max. thickness)) was produced in the Restoration Laboratory of the Römisch-Germanisches Zentralmuseum (RGZM) and used as a reference for the production of further glass copies. For this experiment, 234 points were used in the various trials. A Levallois point was chosen as a model for this study for two main reasons: 1) Levallois points were used previously in experiments (Plisson and Beyries, 1998; Shea et al., 2001; Sisk and Shea, 2009) and are one of the most obvious candidates for weapon tips present in Neandertal and archaic modern human technology over large geographic and time spans; and 2) simple, convergent unifacial flakes such as Levallois points are fairly common in stone technologies around the world (e.g., in the African MSA, Near Eastern Middle and Upper Paleolithic, European Late Glacial, etc.) and the results presented here can be generalized to other similar technologies.

The copies were made from soda-lime glass and were pressed in a waffle-iron-like steel form (see Fig. 1). Although the overall shape of the points is visually identical, one caveat of this method is that when the form was closed, small droplets of glass flowed out of the mold on the sides and the edges of the points needed to be subsequently filed on the ventral side in order to avoid having jagged irregularities. This adds to the convexity of the ventral side of the points, departing from the shape of a simple Levallois point, but because the same treatment was applied to every point, the similarities between them are sufficient to control for morphology. In order to further 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).

2.3. Shafts

The points were slot-hafted 2.5 cm deep into 6 cm-long homogeneous wood foreshafts, using natural beeswax as a binding agent. Natural beeswax is known from ethnographic as well as Paleolithic archaeological contexts (d'Errico et al., 2012) and presents the advantage of 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. The slots were measured and machined to accommodate as close as possible to identical hafting arrangements. The distal end of the slots was tapered at an identical 45° angle so as to not impede penetration into the target. The main shaft of the spear is a 51 cm-long hollow aluminum tube, provided with a cap at the distal end, where it joins the foreshaft, which provides the resistance necessary for propulsion with compressed air. A 245 g cylindrical metal weight was glued to the foreshaft in order to provide additional weight, resulting in an average total weight of 266 g for the hafted spear. This total weight is fully within the range of ethnographically known throwing spears and spearthrower darts (Hughes, 1998; Palter, 1977).

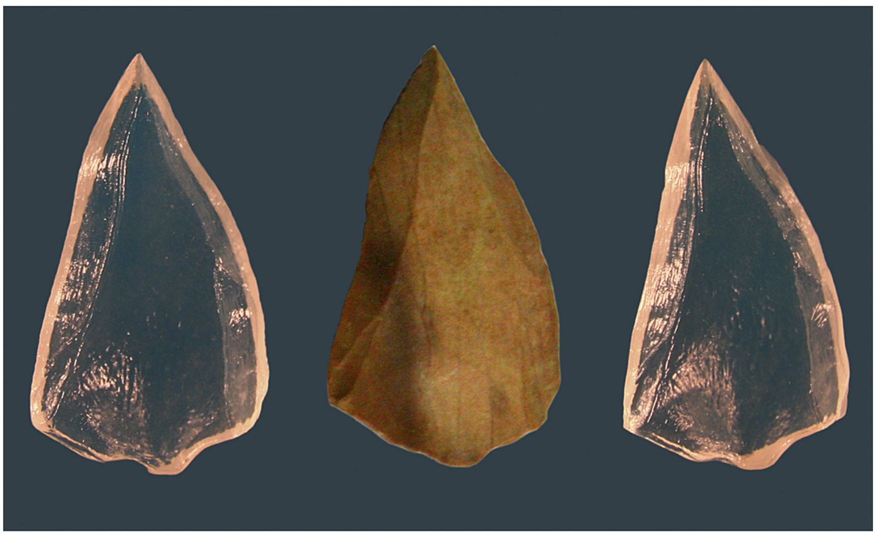

Fig. 1. Original Levallois point and two glass copies.

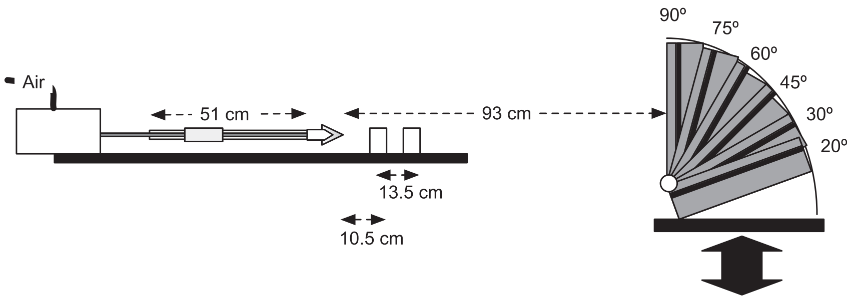

Fig. 2. Schematic drawing of the experimental setup.

2.4. Firing mechanism

The spears were shot using a compressed air gun (Franke and Jäger, 2004) capable of pressures between 1.25 and 15 bar, resulting in projectile speeds (for the 266 g spear) between ca. 7 and 30.5 m/s (see Supplementary Video).

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2013.01.031.

A lanceolate tube with four equally spaced metal guiding rings was flanged to the mouth of the air-gun. The guiding rings reduce friction between tube and spear and aid in keeping the free-flight trajectory as straight as possible and to minimize the effect of trajectory curvature on the IA, which is otherwise determined by the position of the target. At pressures under 1.25 bar (resulting in velocities <7.5 m/s), the trajectory of the spear begins to curve significantly, and the results are not reproducible. In front of the air-gun, the spear passes two laser light curtains and photodiodes that send their signals to a transient-recorder (MF Instruments GmbH) with a time resolution of 0.1 µs. The device measures the time it takes for the tail of the spear to pass through the two laser curtains and calculates the speed using the distance between them (13.5 cm). Because the projectile is elongated, the measurement can only succeed if the tail of the spear is fully out of the second laser before the tip hits the target. For this reason, the target was set 93 cm away from the tip of the spear, which was the smallest possible distance. This results in an extra 24 cm of 'superfluous' airborne trajectory before it hits the target, which we deem to be relatively negligible in terms of changing the IA and the final velocity. In addition, shots at either end of the air pressure range show a certain variation in the recorded speed between repeated trials, due to random deceleration in the slow range and differential pressure loss between chamber loading and release in the fast range. Nevertheless, because the laser curtain measurements do record precisely the speed of each trial, no information was lost.

All spears were oriented such that the dorsal surface faced to the right of the axis of shooting, a choice dictated by the fact that this configuration obtained a better signal from the light curtain. No rotational motion of the spear was detected in any of the videos, nor on high-speed photographic images taken on a trial at ≈12 m/s impact speed.

The largest final velocity produced by our air gun (≈30 m/s, 110 km/h) corresponds to some of the faster atlatl-delivered darts (Hughes, 1998; Raymond, 1986; Stodiek, 1993). 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), 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, our highest values overlap with the lower range obtained by that study. Considering 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. Impacts resulting from spear thrusting are much slower and involve a constant or increasing force applied for longer times, making them unsuitable for testing with this machine.

2.5. Target

The target is fastened onto a 22 kg steel box (see Fig. 2), featuring an inner compartment which pivots around an axle at the bottom, allowing the control of the IA 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 in order to mimic the position of a bone within 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.

2.6. 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 labeled plastic bag. The experiment number was written next to the relevant mark on the target bone plate. If the latter was shattered, the pieces were collected and placed in a labeled plastic bag. The measurements were made with the aid of a digital caliper and the identifications aided by the use of a stereomicroscope (Leica M420) at magnifications 12–48 ×. Photographs were likewise made through the microscope using a T-mount adapter for a Canon 40D digital reflex camera. The fracture types were categorized according to a mixed typology derived from 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). We used six major categories of damage:

3. flute-like (subsumed under longitudinal)
4. burin-like (subsumed under longitudinal)

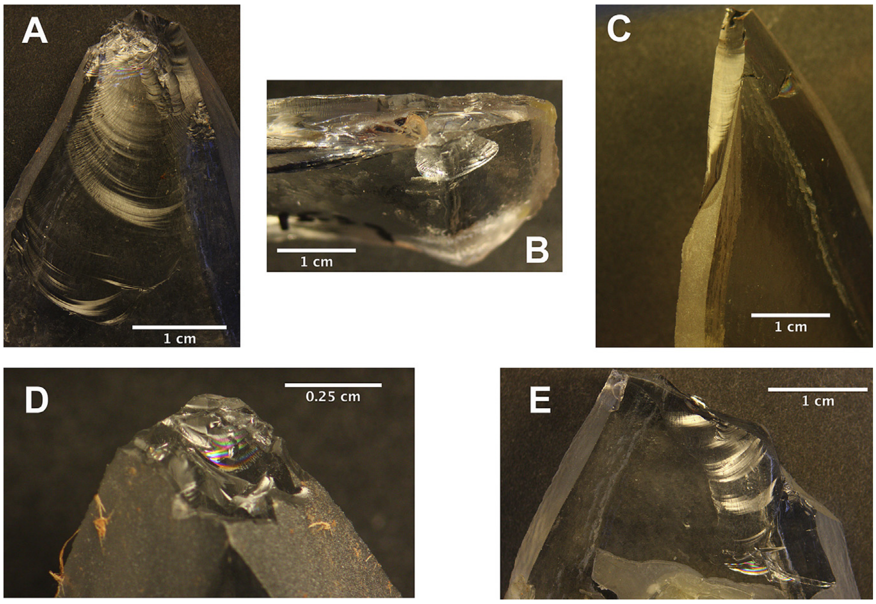

Fig. 3. Major fracture types: A – longitudinal 'flute-like' fracture (with other minor fractures); B – undetached spin-off on a transversal fracture; C – 'burin-like' longitudinal macrofracture; D – multiple step and hinge fractures; E – transversal fracture.

5. transverse/snap
6. spin-off
7. tip crushing
8. 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.

3. Results

The experiments yielded types of fracture that are qualitatively comparable to those reported by previous studies, both experimental and archaeological (e.g., Ahler, 1971; Barton and Bergman, 1982; Bergman and Newcomer, 1983; Bradley and Frison, 1987; Fischer et al., 1984; Moss, 1983; Odell and Cowan, 1986; Plisson and Beyries, 1998; Sano, 2009; Shea et al., 2001; Shea, 1988; Villa et al.,

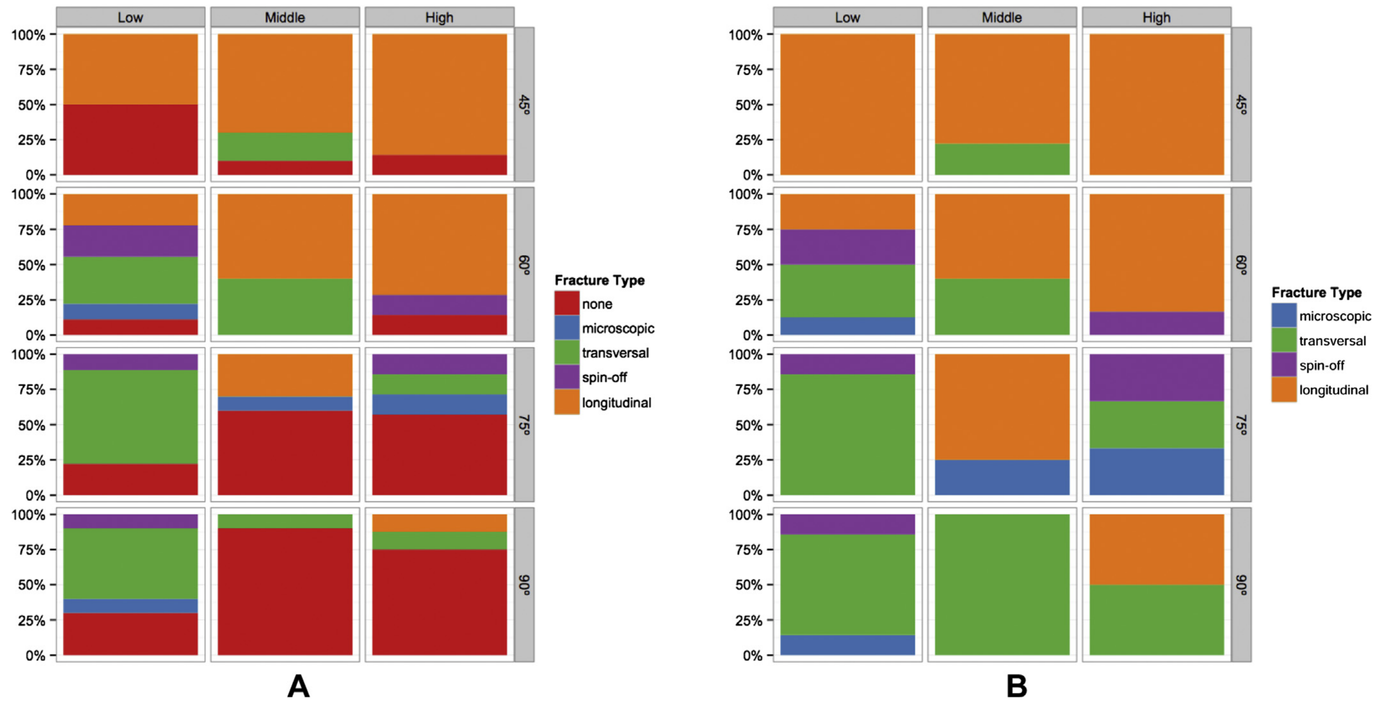

Fig. 4. Proportions of fracture types by angle in three sets of 10 repetitions at ≈9.5 m/s (Low), ≈15.5 m/s (Middle), and 28 m/s (High) speeds. A – including undamaged points, B – excluding undamaged points. Graph generated with ggplot2 package in R (Wickham, 2009).

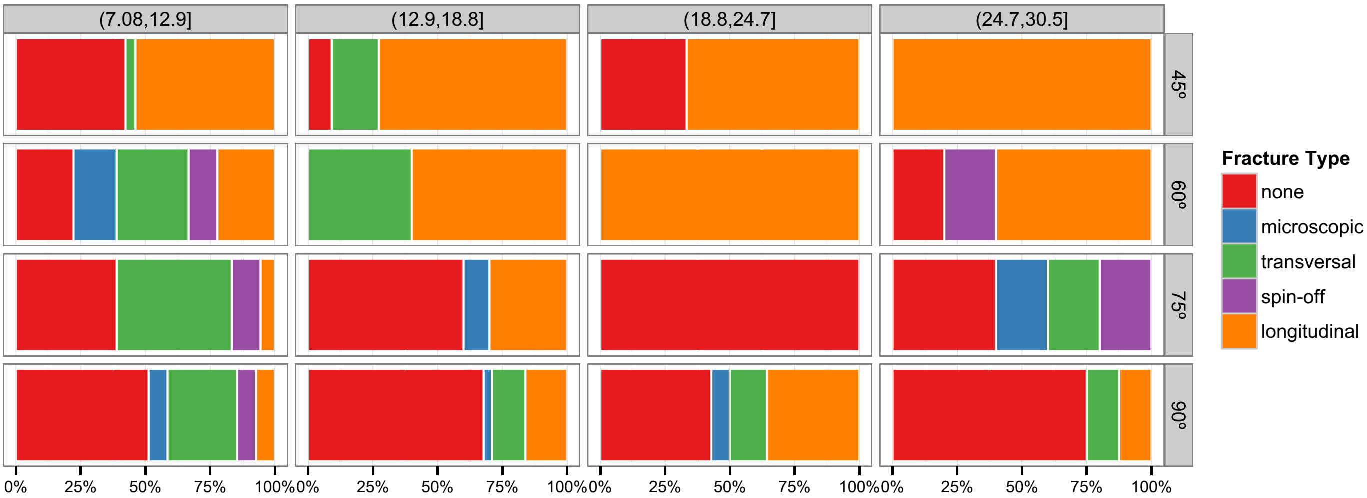

Fig. 5. Proportions of fracture types by angle and speed (in four equal intervals from ≈7 to 30 m/s). Graph generated with ggplot2 package in R (Wickham, 2009).

2009; see also Fig. 3), indicating that the introduction of several artificial constraints on the study design does not affect the realistic nature of the results.

Second, it is important to note that all of the known fracture types were produced by single shots on the target. Repeating the shots until visible damage is observed is one of the common features of previous experiments, but, since standardizing target condition between shots was not deemed possible, it was not systematically attempted in our trials.

3.1. Reproducibility

Fractures formed primarily on the ventral surface of the points. Overall, 43% of all fractures occurred on this surface, and only 9% on the dorsal surface and 7% on one of the edges, with the rest taken up by transversal or microscopic fractures. Of the longitudinal macrofractures, 76% occurred on the ventral surface, and 4% on the dorsal one. To further test the reproducibility of the results obtained with our setup, we performed three series of 10 identical shots at ≈9.5 m/s (low), ≈15.5 m/s (middle), and ≈28 m/s (high, also the maximum reliable speed produced by the air gun). Fig. 4 below shows that, although for the high-speed range and especially for the acuter angles at higher speeds the results are fairly consistent, a certain amount of variability is present in all trials. This effect is probably due to the influence of factors that are difficult to control (such as where exactly the spear hits the plate, or how much the plate moves locally at the time of impact), but also to the fact that our categories are not independent (for example, spin-off fractures are a type of secondary fracture that is dependent on there being a transversal fracture first).

The likelihood that a fracture will occur to begin with influences reproducibility quite strongly, as the two graphs in Fig. 4 demonstrate. This is particularly relevant for the case of mid- and high-speed perpendicular impacts (IA = 90°), where the plate breaks almost every time (see also section 7.3 for further discussion), and for low-speed oblique impacts (e.g., IA = 45°), where the spear has a chance to glide along the surface, without the tip breaking. In these cases, the number of impacts where a fracture was obtained was small enough that it is difficult to judge the reproducibility in terms of fracture type.

3.2. Fracture type as a function of velocity and IA

Since velocity and kinetic energy are equivalent, given a constant mass, we will discuss all the results in terms of the velocity. We report here on the results of increasing the velocity from ≈7 m/s to ≈30 m/s and the IA from 45° to 90°. Trials were also carried out with the fifth angle setting, 30°, but no fractures were ever recorded, and are therefore not included in the analyses presented here. In general, decreasing the IA and increasing the velocity have a similar effect: the creation of proportionally more longitudinal macrofractures (see Fig. 5 below). This can be explained in a simple

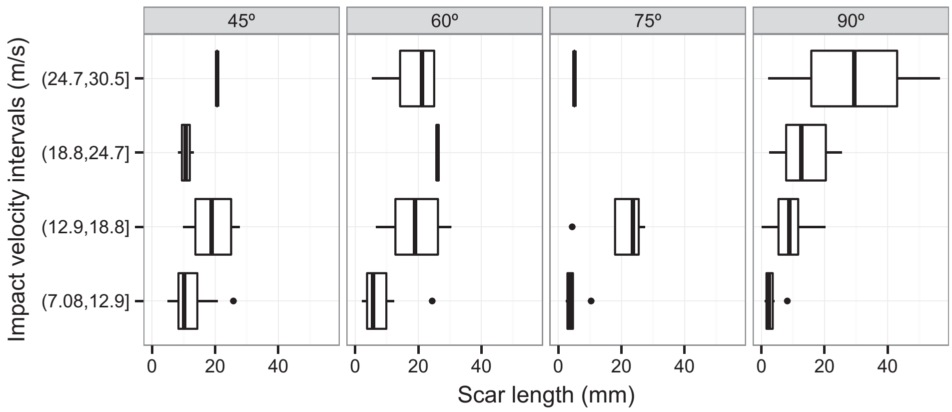

Fig. 6. Boxplots showing scar length for each of the four equal speed intervals and each of the four angle settings. Graph generated with ggplot2 package in R (Wickham, 2009).

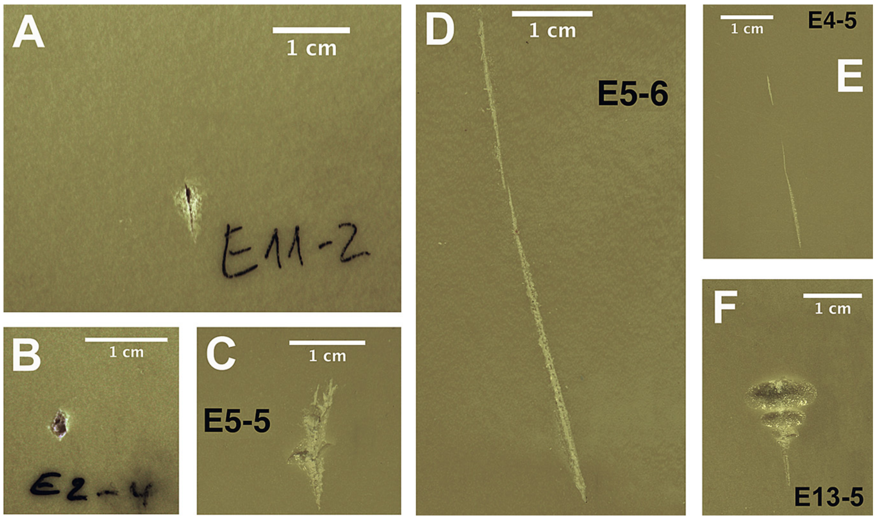

Fig. 7. Major types of marks recorded on the polyurethane bone plates. A – indented; B– tip embedded; C – tip embedded + linear; D – linear; E and F – skipping. Shattered plate not shown. Graph generated with ggplot2 package in R (Wickham, 2009).

way, using knowledge gained from controlled experiments in flake production (e.g., Dibble and Rezek, 2009; Dibble and Whittaker, 1981; Pelcin, 1997; Speth, 1972). As the impact angle decreases, provided the tip shape stays constant, comparatively more of the 'side' or edge is hit at once by the bone surface, hence increasing the 'platform' thickness. This is known to produce larger flakes, when all the other factors are held constant.

Another trend appears to be a reduction in the frequency of transversal tip breaks as speed increases. This is probably due to the greater likelihood of target penetration with the higher speeds, leading to most of the forces aligning along the axis of the shot. Spin-off fractures, identified by Fischer et al. (1984) as one of the two types of diagnostic fractures (provided they are >6 mm long), are only very sporadically present in the low and high-speed segments. However, none of the high-speed spin-off fractures are longer than 6 mm. Since the exact mechanism for the formation of such fractures has never been documented in detail, it is difficult to provide anything beyond speculations regarding the cause of this pattern.

3.3. Fracture size as a function of velocity and IA

Regarding the size of the fractures, the expected pattern is only obvious in the 90° angle trials – scar length increases with impact velocity ($p < 0.01$, $R^2 = 0.72$, df = 12, if only longitudinal fractures are taken into account). In the other angle trials, the trend is less clear, although the slowest impacts do seem to stand out with very small fractures. The overall relationship between scar length and velocity, without taking angle into account, is significant but very weak ($p < 0.01$, $R^2 = 0.27$, df = 56).

This result again confirms knowledge gained from the flint-knapping experiments mentioned above, namely that platform attributes (in this case, the size of the contact area between projectile tip and target) partly determine the size of a flake, provided sufficient force is applied for the detachment. Thus, for certain platform configurations, any additional force will not make a difference in terms of the size of the produced flake (Dibble and Rezek, 2009). For this reason, we observe the convergence in damage size between tips broken in low-speed impacts at acute IAs and tips broken by high-speed impacts at higher IAs.

3.4. Relationship between types of impact and target marks

The six major types of marks left on the polyurethane bone plates are presented in Fig. 7 below. Many plates were also simply cracked and shattered on impact (not shown here).

Fig. 8 shows the proportion of marks on plates by the same four speed intervals as in Fig. 5. Some very clear patterns emerge:

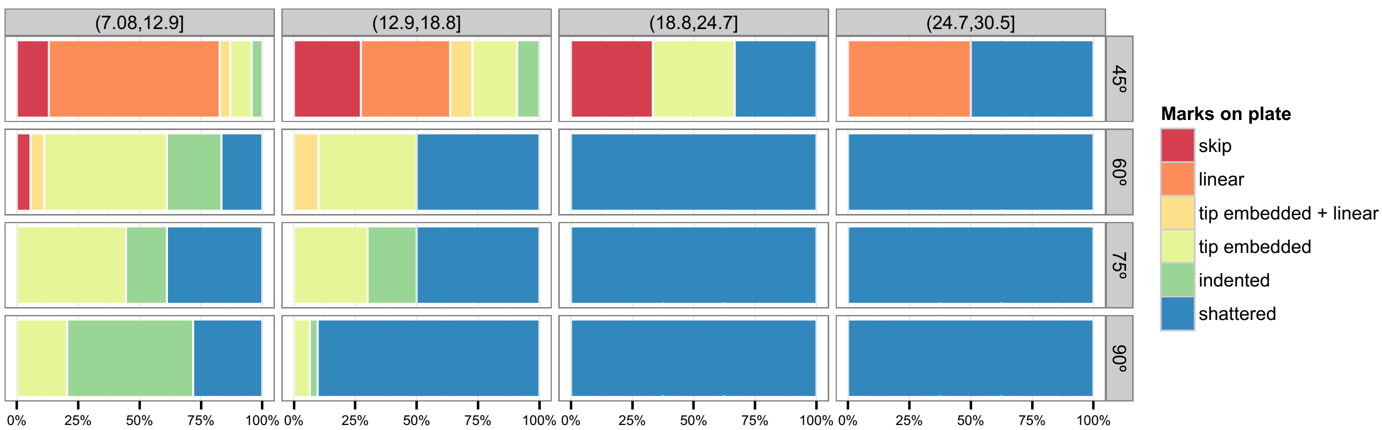

Fig. 8. Proportions of plate marks for each speed interval and angle setting. Graph generated with ggplot2 package in R (Wickham, 2009).

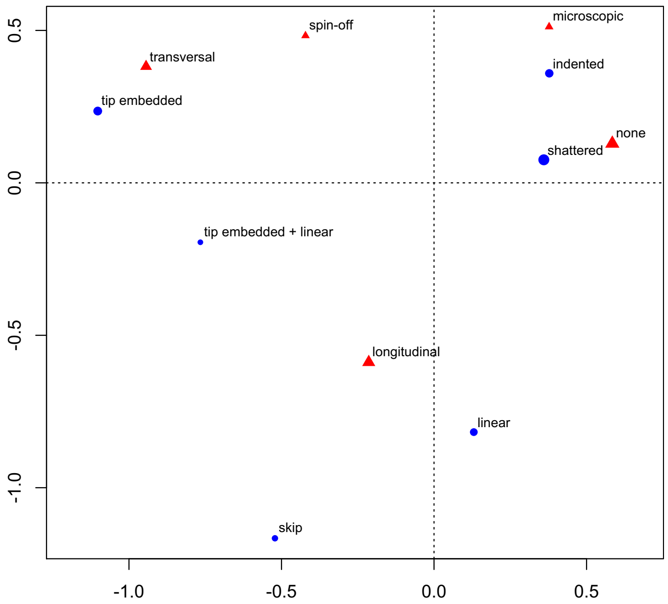

Fig. 9. Correspondence analysis plot of Dimension 1 (*x*-axis, 62.7% of the variance) and Dimension 2 (*y*-axis, 29.4% of the variance) showing the relationship between impact fractures and plate marks. Triangles represent projectile tip damage and circles represent marks on the plates. The size of the points is proportional to their frequency. Graph generated with ggplot2 package in R (Wickham, 2009).

1) At low speeds, tips penetrate and leave an indentation, and either break off in the plate or come out unbroken;
2) As the speed increases, the likelihood of shattering the plate increases;
3) As the IA decreases, tips tend to penetrate, break off, and continue to skid along the plate, leaving cut-mark-like traces.

The combination of these three patterns allows us to hypothesize on how projectile tip fractures most likely occur:

1) At low speeds, and especially with perpendicular impacts, we expect more transversal bending fractures, as tips do not have the energy to penetrate and stay temporarily embedded in the bone, later breaking off due to the spears' own weight.
2) At higher speeds, we expect either no breaks at all, or longitudinal breaks with bending initiations, resulting from either oblique or perpendicular impacts, depending on the resistance of the target. Secondary fractures could also appear from this category, especially from high-speed oblique impacts, where the distal tip breaks but the spear continues along its original path, possibly skipping along the target.

In order to test this assumption, we carried out a correspondence analysis, the results of which are displayed in Fig. 9. Most of our expectations are confirmed, with transversal fractures closest to embedded tips, and shattered and indented plates closest to undamaged points. Longitudinal macrofractures also plot expectedly closest to the linear trace pattern, but spin-off fractures do not appear closely associated with skipping or embedded tips. This suggests that Fischer et al. (1984) hypothesized correctly regarding the origin of spin-offs in secondary impacts between distal and proximal parts of the tip following a transversal fracture, rather than in secondary impacts with the target.

Finally, because many researchers, following Fischer et al. (1984) rely on the use of 'step-terminating bending fractures' as a DIF, we recorded and analyzed the proportions of each type of initiation and termination. Cone initiations appear more frequently in the 90° impacts when the plate shatters, although they are also present in most of the other trials (see Fig. 10 above). However, bending initiations are by far the most common type, and it is difficult to speak of any strong association between plate mark and initiation type. Furthermore, our study cannot confirm the existence of any relationship between flake termination and speed or angle, with feather, hinge, or step terminations being present in all trials (see below Fig. 11). Snap-terminating damage is characteristic of transversal breaks and therefore appears more frequently in the perpendicular impacts, especially those at low speed, but

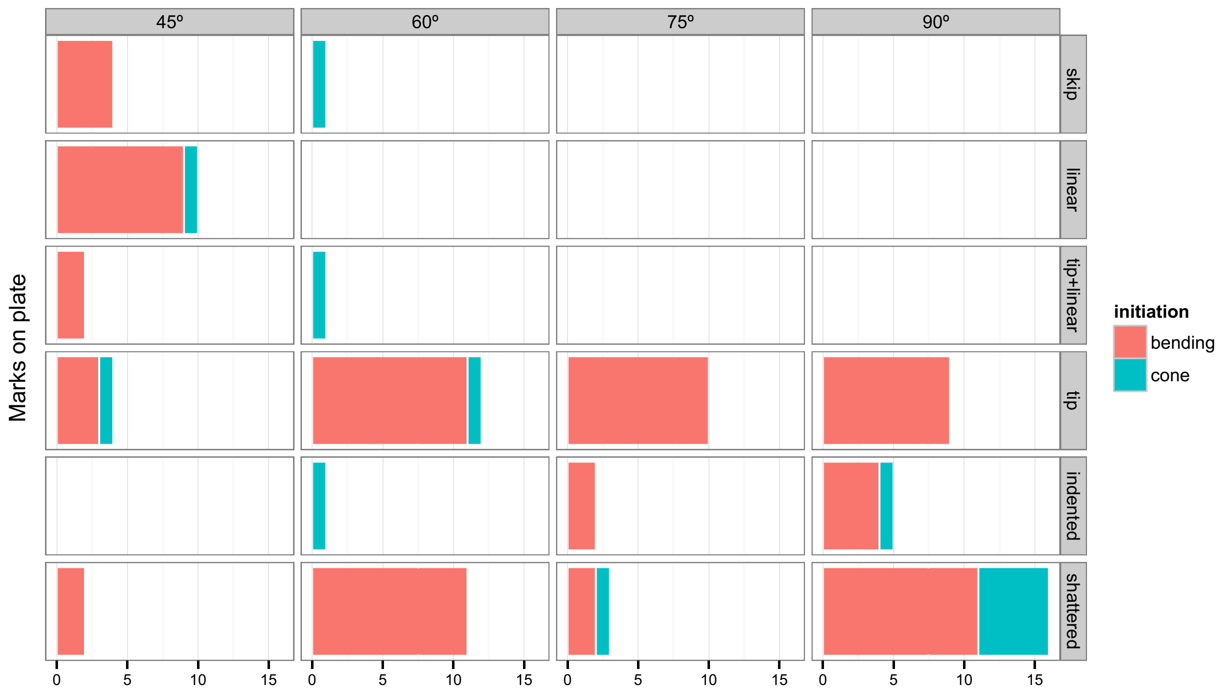

Fig. 10. Raw frequencies of initiation types for primary macrofracture types (spin-offs excluded), tabulated by type of mark left on the plate. The overwhelming majority of fractures are of bending type, with the highest proportion of cone initiations in the perpendicular (90°) shot trials where the plate shatters. Graph generated with ggplot2 package in R (Wickham, 2009).

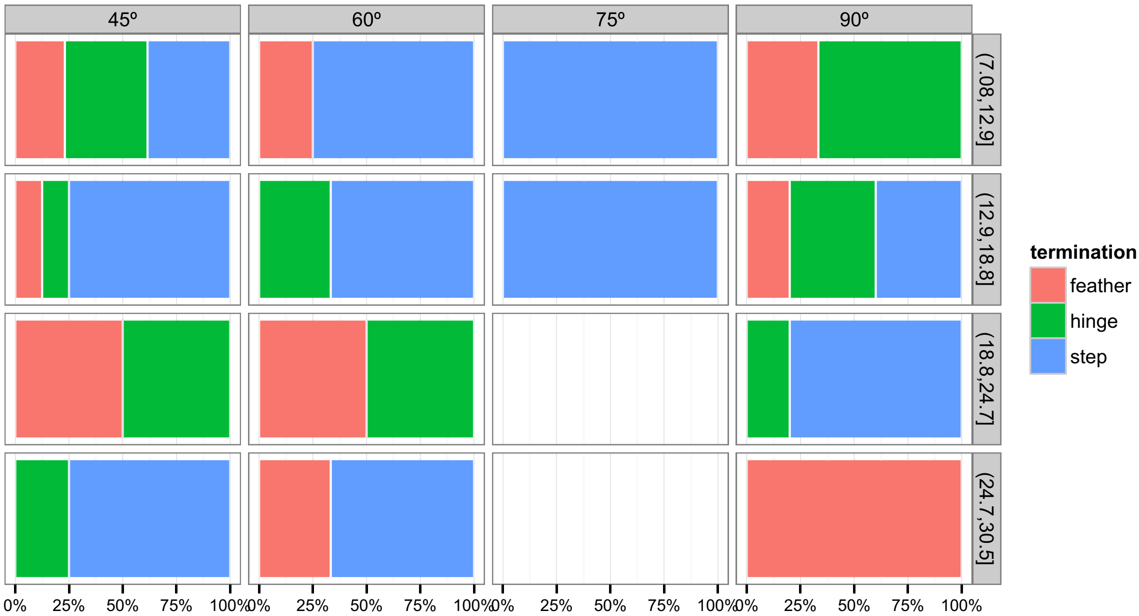

Fig. 11. Percentages of termination types (hinge, feather, and step) by speed interval and angle. These were calculated only for longitudinal macrofractures. Note the high frequency of feather terminations in the high-speed 90° trials. Graph generated with ggplot2 package in R (Wickham, 2009).

transversal breaks are not considered DIFs by any researchers. Based on these results, we suggest that the initiation and termination attributes be dropped from the list of diagnostic features of weapon tip damage.

4. Discussion and conclusions

In the course of our experiments, we were able to replicate the types of damage produced in less standardized experiments (involving animal carcasses and flint replicas), while also providing rigorous constraints on the relevant causal factors. Of the established DIFs, longitudinal macrofractures ([pseudo]-burin-like and flute-like fractures) become more frequent as speed increases and as the impact angle decreases. Likewise, transversal (snap) fractures are more common in slow impacts. Greater speeds do result in larger damage, but slow, oblique impacts can also lead to tip macrofractures in the same size range. Nevertheless, given a sufficiently large sample, mid- (15–20 m/s at impact) and high-speed (25–30 m/s at impact) range projectile tips could be distinguished based on damage size from low-speed ones (below 15 m/s at impact), although no difference between the upper two ranges would be detected, unless the angles were kept constant.

In a more realistic setting however, it is likely that this convergence would lead to an even greater overlap, because animal targets are not homogeneous. This means that even very fast projectiles are likely slowed down by soft tissue to different degrees before hitting bone (depending on the thickness of the soft tissue at the point of entry). In our own experiments, even the fastest projectiles were sufficiently slowed down by the gelatin that they did not come out of the back of the target. Consequently, slowly delivered projectiles might hit a bone close to the skin at the same speed as fast-delivered projectiles would hit a bone deeper in the body. An interesting corollary of this is, however, that many mid- and high-speed impacts should also result in a large number of projectile tips embedded in animal bones, as is typical for many of our slower impacts. Unfortunately, such evidence is frequent only in the later periods of the Stone Age (e.g., Bratlund, 1996; Noe-Nygaard, 1974), although a few cases from the Middle (Boëda et al., 1999) and Early Upper Paleolithic (Münzel and Conard, 2004) are also known.

Spin-off fractures (Fischer et al., 1984), which are considered to be one of most distinctive DIF types for projectile use, were only sporadically observed in this experiment (see Fig. 3), and no pattern for their distribution can be identified. At this point we can only speculate on why that may be. If Fischer et al. (1984:24, Fig. 6) are correct in concluding that (large) spin-off fractures are created due to secondary impacts between the distal and proximal parts of the point subsequent to an initial, transversal fracture, then we would expect them to be more frequent with increasing kinetic energy/speed of the launched projectile. Since this is not the case in our experiment, we propose two explanations. First, it is possible that in experiments with real animal carcasses, secondary impacts are more common due to the presence of multiple layers of bone (e.g., ribs on both sides of the thoracic cavity) or to the presence of lithic debris from previous shots (or both). Alternatively, our lithic points are, because of their shape, less prone to transversal breaks to begin with than those used by Fischer et al. (Brommian points are made on blades, whereas our Levallois point has the geometry of a flake) and by other studies that noted spin-offs (e.g., Lombard et al., 2004). If the former is true, the high frequency of spin-off could be an artifact of the experimental protocols (multiple shots into the same target with the same weapon) rather than a real feature of hunting damage on projectile points. It is worth noting that several experimental studies did not note spin-offs at all (e.g., Odell and Cowan, 1986; Shea, 1988), suggesting that more experiments investigating the influence of tip shape and target homogeneity on the production of this type of wear are needed.

Finally, we argue that the use of ‘step-terminating bending-initiated’ longitudinal fractures as diagnostic of impact is not entirely justified. Bending initiations are by far the most common type in our experiments, but that can be explained easily without referring to weapon impacts. Making the analogy with flintknapping again, especially in the case of ‘glancing’/oblique trials, the ‘hammer’ (in this case, represented by the bone target) is much larger and much softer than the ‘striking platform’ (the core being here the glass tip). Therefore, the fractures occur as a result of a load that is distributed over a larger surface rather than concentrated in one point. This is exactly the reasoning of Fischer et al. (1984), but while this situation is typical of impacts between brittle points and soft organic material, we can imagine many other contact situations that would lead to producing bending fractures on the relatively fragile tips of pointed flakes. For Levallois points, this is supported by the results of Plisson and Beyries (1998), who conducted butchery tasks with replicas of Levantine Levallois points and concluded that non-weapon uses could not be ruled out. We recommend that archaeological candidates for interpretation as weapon tips should be extensively tested in basic tasks that involve minor impacts, such as, chopping and dismembering carcasses, etc., in order to investigate the frequency of bending tip macrofractures that are not related to weapon impacts.

As for terminations, those of step-type account for 55% of the total for longitudinal macrofractures, with the rest exhibiting 26% hinge and 18% feather terminations. However, all three types are represented in all angle and speed trials, at various proportions. Since none of the known mechanisms for the production of flake terminations can be reliably linked with conditions that are unique to high-speed impacts, we cannot see any good reasons to regard step-terminating bending macrofractures as diagnostic of weapon use.

The presented results suggest that the problem of reconstructing delivery systems for prehistoric stone-tipped weapons is more difficult than anticipated. The desired tripartite classification normally used in archeology to distinguish hand-thrown spears (javelins) from spearthrower darts and arrows requires clear demarcations between the weapon types. Although we are able to distinguish between the extremes of the speed spectrum based on the frequency of longitudinal fractures and their size, archaeological samples will surely contain more variation and, hence, will be more difficult to distinguish. The task of identifying weapon technology will be dependent on having sufficiently big differences to detect, and that, in turn, will be dependent on having very large sample sizes. The problem of sample size is particularly relevant for archaeological assemblages with high resharpening indices, where it is likely that many broken weapon tips would have been recycled into other tools, thus disappearing from the archaeological record.

With respect to Middle Paleolithic weaponry, especially if Neandertals are the putative makers, there seems to be a consensus that they did not possess high-speed launching technologies (aided by mechanical devices). Both skeletal evidence (Rhodes and Churchill, 2009; Schmitt et al., 2003) and ballistics-inspired studies on the feasibility of using Levallois and other Neandertal-made points as weapon tips (e.g., Shea and Sisk, 2010; Sisk and Shea, 2009) seem to point in the direction of thrusting or low-velocity throwing spears rather than high-speed 'complex' projectiles (sensu Shea and Sisk, 2010). Several previous studies (e.g., Fischer et al., 1984; Lombard et al., 2004; Plisson and Beyries, 1998) reported some differences between the frequency of types of impact fractures obtained in experiments with thrown v. thrusted spears, but sample sizes were small and more research into this topic needs to be done to be certain of it. It is very likely, however, that any thrusting spears would also have been occasionally thrown, making it likely that hand-delivered weapon technologies would exhibit a mixed signal in the archaeological record.

Because of the problems outlined above, approaches that focus on the identification of extreme events may prove more fruitful. A current study within our own research program is testing the applicability of reconstructing loading regimes by using secondary fracture features such as Wallner lines (cf. Hutchings, 2011) to calculate the speed of fracture propagation. Further, in order to correctly distinguish between thrusting and flight-based weapons, we are investigating the effect that thrusting, as a delivery system that combines low-speed, high-impact energy with a follow-through motion would have on the fracture patterns. In tandem with faunal work on hunting strategies, such studies will help to advance our understanding of the comparative technological capabilities and efficacy in hunting of various Pleistocene hominin groups.

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