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Projectiles Under a New Angle: a Ballistic Analysis Provides an Important Building Block to Grasp Paleolithic Weapon Technology

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Abstract

Weapons and past weapon systems are important research topics in Paleolithic archaeology. Its popularity stems from its relevance for understanding broader technological evolution, subsistence strategies, and human behavior. However, identifying what weapon system was used has proven to be a significant methodological challenge over the last few decades and in spite of what some titles of recent publications suggest, the question is still not resolved. In this paper, we present the results of a ballistic analysis of the four modes of propulsion that are traditionally considered for the Paleolithic period (bow, spear-thrower, hand-cast and thrusting spear). We advocate a stepwise approach to the problem given the multiple variables involved. The goal of this study is to add an essential building block to current understanding by exploring the notion of reactional impact stress (RIS) on the basis of the angle of incidence developed by the different projectiles. Our results show the importance of RIS for accurately understanding the projectile impact phenomenon and the existence of a reproducible and mutually distinct RIS between the four tested weapon systems. These results shed a new light on approaches that have been used previously to examine weapon systems archaeologically, such as those relying on the length of "diagnostic impact fractures". Our results allow the proposition of an alternative approach that appears to hold great potential, in particular for identifying the use of the bow. While a reliable method for recognizing past propulsion modes is not yet established, we conclude that the solution lies within the integration of several fields, more in particular use-wear analysis, fracture mechanics in brittle solids, and ballistics and we progressively move forward in identifying the key building blocks of such a method.

Keywords Propulsion mode · Stone-tipped projectiles · Ballistics · Fracture mechanics · Use-wear analysis Experimental archaeology

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Introduction

Hunting weapons and their mode of propulsion are important issues in prehistoric archaeology and their study has proven to be a methodological challenge that has raised multiple questions (Rots & Plisson, 2014). The evolution of prehistoric weaponry plays an important role in current debates on human evolution and the appearance of long-range weapons has been used as a key factor to explain the success of modern human dispersal in Eurasia (Sano et al., 2019; Shea & Sisk, 2010).

Accurately documenting changes in prehistoric weaponry is fundamental for several reasons including the fact that the type of weapon used significantly affects the hunting and subsistence strategies that human populations may develop. Given the central role of hunting in prehistoric life, an improved understanding of the weapons and weapon systems used and the hunting strategies developed is indispensable for insight in prehistoric human behavior. Animals undoubtedly provided the main sources of protein intake and the techniques and know-how involved in guaranteeing this provisioning directly reflect an essential and likely time-consuming aspect in the life of these populations (Bleed, 1986; Ellis, 1997; Greaves, 1997; Lee, 1968).

Few organic remains of Paleolithic weaponry have preserved and these only punctuate the history of the evolution of this technology with a few reference points. The oldest examples are the wooden spears and spear fragments from the Lower and Middle Paleolithic sites of Schöningen (Thieme, 1997), Clacton-on-Sea (Oakley et al., 1977) and Lehringen (Movius, 1950), the spear-thrower hook recovered from the site of Combe-Saunière and (tentatively) attributed to the Solutrean (Cattelain, 1989), the Epipaleolithic arrows of Stellmoor (Rust, 1943), and the Mesolithic bow of Holmegaard (Junkmanns, 2013). Spear-thrower hooks are more abundant in the Magdalenian (e.g., Cattelain, 2005) and other bows exist for the Mesolithic period (e.g., overview in Sachers, 2009). These fragments as exceptional as they are only provide a very fragmented view on a possible evolution in prehistoric weaponry that is by no means complete or representative of the likely variation and complexity in weaponry that once existed. Moreover, the finds are all located in Western Europe and can by no means considered representative for global evolutions in weaponry.

In spite of the fact that points in organic material exist and may be abundant on occasion, their frequency depends on particular preservation conditions. Stone points have the advantage to be more systematically present and thus provide a means to a more complete picture of prehistoric weaponry and its evolution through time. Relying on these stone points for such purposes nevertheless presents a number of important methodological challenges and over the years, different approaches have been developed and tested, first focused on the identification of projectile points, but more recently also focused on the identification of past propulsion modes. While a reliable method to identify projectile points has been developed within the context of use-wear analysis, this is not the case for what concerns propulsion modes for the moment (Rots & Plisson, 2014; Coppe et al. In prep). The proposed approaches and attempts have definitely nourished debates, but none was successfully developed into a reliable and verified method permitting the recognition of past propulsion modes (see Coppe et al., In prep. for a complete overview of these approaches including their potential and limitations). Most approaches tested up to now are based on the analysis of impact fractures, but these studies often witness a limited understanding of fracture mechanics in spite of significant efforts invested in this domain a few decades ago (Hayden, 1979). Understanding how a stone point breaks upon impact is essential if one aims to reliably recognize the weapon system behind a particular fracture pattern on a stone point.

In addition to an understanding of fracture mechanics in brittle solids, we have also emphasized the importance of integrating ballistics in projectile studies (Coppe et al., 2019). Previous efforts to understand the ballistic behavior of prehistoric projectiles have focused on aspects such as weapon performance (precision, penetration, distance, kinetic energy, speed) (Carrère & Lepetz, 1988; English, 1930; Milks et al., 2016; Schmitt et al., 2003; Strickland & Hardy, 2005; Waguespack et al., 2009; Whittaker, 2013; Whittaker et al., 2017; Wood & Fitzhugh, 2018) and the behavior of the projectile at release or in-flight (Coppe et al., 2019; Klopsteg, 1943; Kooi, 1998; Lepers, 2010, 2016; Strickland & Hardy, 2005; Whittaker, 2016; Whittaker et al., 2017). Research intensity varies significantly depending on the mode of propulsion and the bow was definitely investigated most, which contrasts with the very limited number of studies focused on thrusting spears (for some exceptions, see Coppe et al., 2019; Milks et al., 2016).

When projectiles are studied, the focus generally either lies on a ballistic application or on the functional examination of armatures and few combined attempts can be noted (but see Clarkson, 2016; Geneste & Plisson, 1990; Hutchings & Bruchert, 1997; Iovita et al., 2014, 2016; Sano & Oba, 2015). Combined studies are most often framed within the context of the identification of propulsion modes and two new approaches have been proposed, one based on the length of impact fractures (Clarkson, 2016; Iovita et al., 2014, 2016; Pargeter et al., 2016; Sano, 2016; Sano & Oba, 2014, 2015; Sano et al., 2019) and another one based on the propagation speed of impact fractures (Hutchings, 2011, 2015; Sahle et al., 2013). In spite of their undeniable contribution to ongoing debates, their results and their potential for archaeological analyses are still criticized (see Coppe et al. In prep. for a complete review of these approaches).

We advocate a stepwise approach to projectiles and propulsion modes given the complexity of the issue and the multiple variables involved. We consider that each variable should be properly understood in its own right in order to gradually develop a reliable and robust method that permits to identify past propulsion modes. We argue that such a method should integrate use-wear analysis, fracture mechanics in brittle solids, and ballistics. Up to now, two parameters have enjoyed most attention of researchers, the kinetic energy (KE) (Clarkson, 2016; Iovita et al., 2014, 2016; Sano & Oba, 2014, 2015) and the angle of impact (Iovita et al., 2014), with particular attention to the effect of each of these parameters on the length of impact fractures. This effect was judged to be considerable (in particular Iovita et al., 2014) for both ballistic parameters. Such a result perfectly subscribes the theory of fracture mechanics in brittle solids, which states that the development of a crack is influenced by four main parameters: the available energy, the direction in which the stress is applied, the morphology, and the nature of the fissured material (Cotterell & Kamminga, 1979, 1986, 1987; Tsirk, 2014).

In this paper, we take the investigation of these parameters a step further and we explore the conditions of KE and the direction of applied stress, thanks to the notion of reactional impact stress (RIS) and we do this for each of the four modes of propulsion traditionally considered for the Paleolithic (bow, spear-thrower, hand-cast spear, thrusting spear). After having evaluated the KE of each propulsion mode in a previous study (Coppe et al., 2019), we now evaluate whether each propulsion mode produces an RIS that is sufficiently distinctive to permit the recognition of the propulsion mode based on the fractures on the archaeological stone projectile points. To observe potential differences in RIS, we measure the angle of incidence produced by a standard decided upon for each mode of propulsion and we explore the variability generated by parameters like the spine (for arrows and darts) as this could influence the results. We start from the premise that only the combination of ballistics and fracture mechanics provides a means to reconstruct propulsion modes of Paleolithic weapons. Therefore, a fundamental ballistic approach to each weapon system is an essential first step. It should provide the necessary background to accurately understand and describe their ballistic behavior and permit to finally link this behavior with the mechanical response it induces on a stone armature during impact. We argue that this development may present the key to a future reliable method for identifying prehistoric weapon propulsion modes.

Definitions

In addition to KE (see also Coppe et al., 2019), we use different concepts, such as RIS, angle of incidence, and center of mass, each of which we define below.

According to Newton's third law of motion, also known as the principle of action and reaction, a body A that exerts a force on a body B will receive back a force of equal intensity in the same axis but in opposite direction exerted by body B. The same goes for projectile impacts, but in this case the reactional force will generate stress on the stone tip potentially leading to a fracture. We define this stress here as *RIS*. The direction of the vector of this reactional stress is determined by the angle of incidence (see below) of the projectile at the time of impact while the intensity of the vector is determined by the KE of the projectile upon impact. Important is the fact that the RIS is composed of a compressive and a bending component, the proportion of which depends on the angle of incidence of the projectile upon impact.

The *angle of incidence* of a projectile is the angle between the tangent of the trajectory of its center of mass and the axis of its point (Fig. 1). This notion should not be confused with the angle of impact which is the angle between the axis of the point and the surface of the target.

The *center of mass* or center of inertia of a projectile of constant mass is the point where all inertia effects apply. In this study, it can be considered equivalent to the center of gravity.

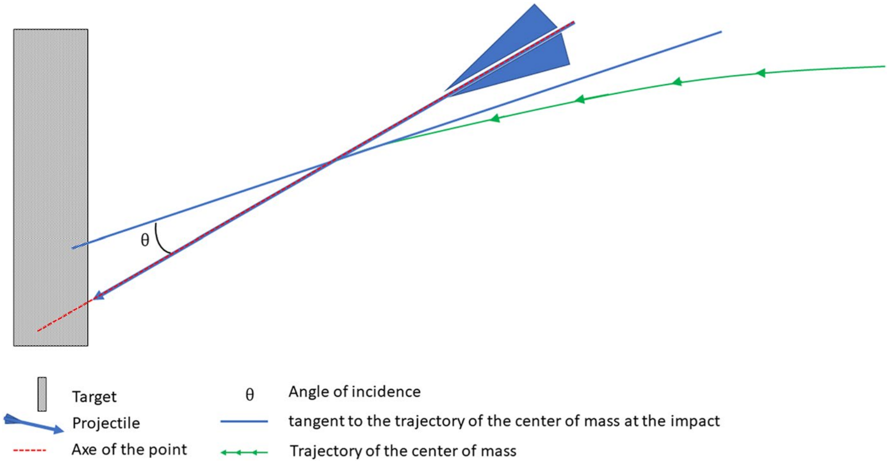

Fig. 1 Angle of incidence

The angle of incidence is a common notion in ballistics when describing the flight of a projectile and known to influence the penetration capacities of the projectile in the target (Dong et al., 2015; Paul Clinci et al., 2019) and its stability in flight (Cotterell & Kamminga, 1992). Here, our interest is focused on the angle of incidence of the projectile at the moment of impact since it will determine the direction of the RIS and thus the proportion of its bending and compressive components. When the axis of the point and the axis of the tangent of the trajectory of the center of mass

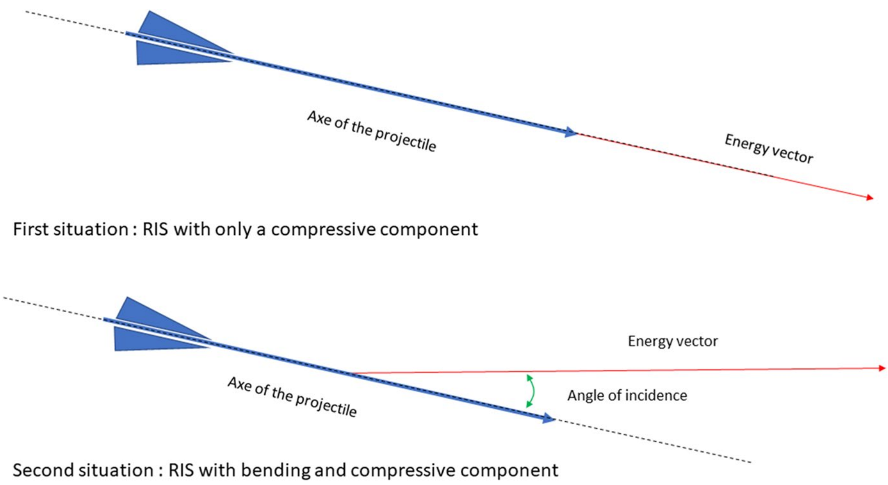

Fig. 2 Illustration of the two possible situations. In the first one, the angle of incidence is equal to 0 and the RIS will be totally oriented toward the compressive component. In the second situation, an ange of incidence is measured and will produce a RIS divided between the compressive and the bending component

of the projectile are aligned at the moment of impact (angle of incidence = 0°), the direction of the RIS will be parallel to the point's axis and thus exclusively oriented toward its compressive component (Fig. 2, first situation). When the two axes are not aligned but secant, the point will be subjected to an RIS with a compressive and a bending component (Fig. 2 second situation). The more the angle of incidence approaches 90°, the higher the bending component of the RIS will be and the lower the compressive component.

External Ballistic Elements

Ballistic analyses divide the behavior of a projectile in three phases. In internal ballistics, the behavior of the projectile before it leaves its propulsion mode is studied. In external ballistics, the behavior of the projectile is studied between release (the moment it leaves its propulsion mode) and the moment it contacts the target. In terminal ballistics, the interaction between the projectile and its target is studied (Bell, 2012). In this study, we focus on the external ballistic elements only and we discuss them for each of the four propulsion modes traditionally considered (i.e., thrusting spear, hand-cast spear, spear-thrower-and-dart, bow-and-arrow).

Bow-and-Arrow

The propulsion phase of an arrow has been a subject of study for a long time and is relatively well known at present. During its propulsion, the shaft of the arrow bends. This phenomenon is called the archer's paradox (Klopsteg, 1943). When an arrow is set on the string and placed against the cheek of the bow, the thickness of the bow handle creates an acute angle between the axis of the arrow and the launching axis (i.e., the axis formed between the string and the center of the bow handle) (Lepers, 2005; Lepers & Rots, 2020) (Fig. 3). Careful calibration of the flexibility (spine) of the shaft allows it to bend adequately under the bending stress that is created when the string pushes on the notch of the shaft at release combined with the resistance against this push generated by the friction against the handle and by the mass of the point (Kooi, 1998). This flexion allows the arrow to round the obstacle of the handle and move toward the target. The correct spine of an arrow depends on the type of bow, its draw weight, and the draw length of the shooter (cf. Lepers & Rots, 2020), and appropriate values can be obtained by consulting a reference table such

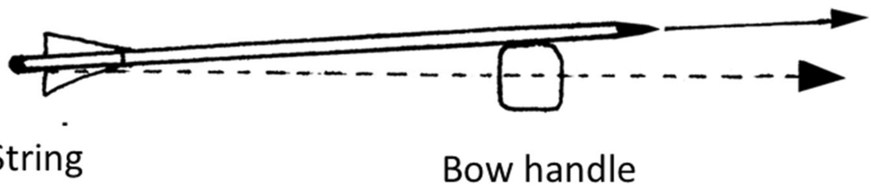

Fig. 3 Offset position of the arrow on a traditional bow without firing window which is at the origin of the phenomenon called the archer's paradox (modified from Fig. 10 in Lepers, 2010)

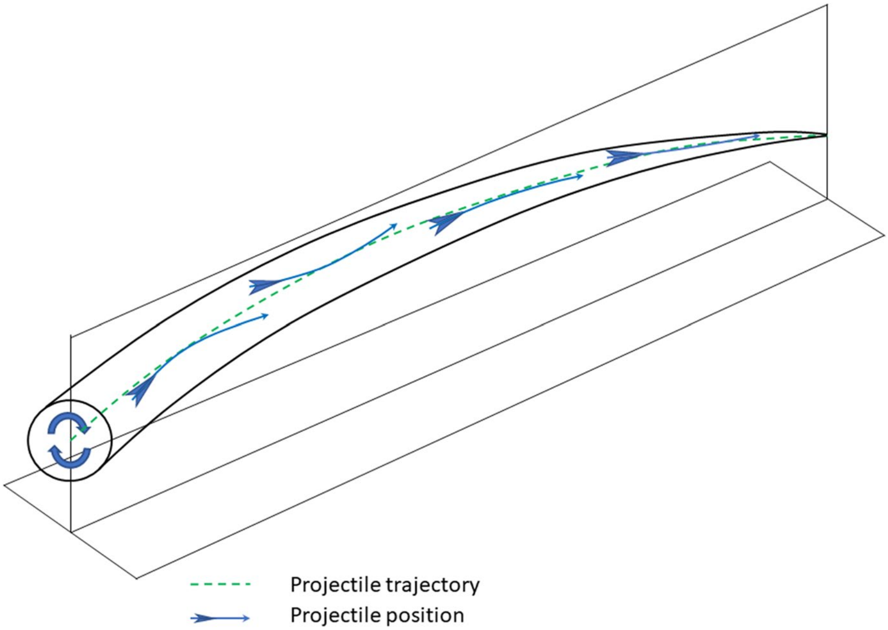

Fig. 4 Sinusoidal rotative movement of an arrow or a dart around its trajectory (modified from Fig. 13 in Lepers, 2010)

as the one produced by Easton (Easton archery, s. d.). A projectile with an inappropriate spine, either too rigid or too flexible, can laterally deviate from its trajectory (Klopsteg, 1943; Kooi, 1998). On modern bows, a notch or a firing window on the bow handle can greatly reduce the archer's paradox (Kooi, 1998). During flight, the arrow partly maintains the sinusoidal oscillation movement acquired at release, but the sinusoidal aspect will gradually decrease along the trajectory (as a function of distance traveled by the projectile) because fletching stabilizes the position of the butt of the projectile (Lepers & Rots, 2020) (Fig. 4 and film 1 in supplementary data).

Spear-Thrower-and-Dart

Similar to the bow, the spear-thrower sets the projectile in motion by a push on its heel and the dart will bend with more or less amplitude during its propulsion phase. This flexion is associated with the initial ascending motion of the hand during the linear part of the propulsion phase and is reinforced by the descending motion of the hand at the end of the elliptical phase and the flip of the spear-thrower at the end of the motion. The amplitude of this flexion is more important in the case of a dart in comparison to an arrow and the sinusoidal oscillation over its trajectory is therefore also more important (film 2 in supplementary data). Again, fletching helps stabilizing the flight of the dart. In ethnographic contexts, fletching is rare to absent, but fletched darts have been recovered archaeologically (Hare et al., 2012). For most authors, proper calibration of the spine is essential for guaranteeing a reliable use of the projectile and it has to be adapted to the acceleration transmitted by the user (Bergman et al., 1988; Pettigrew & Garnett, 2015; Whittaker et al., 2017). A poorly adapted spine could generate a loss of kinetic energy (Lepers, 2010) and a lateral deviation of the trajectory (Hutchings & Bruchert, 1997; Lepers, 2010; Pettigrew, 2015; Pettigrew et al., 2015), though no consensus was yet reached for this last element (Whittaker et al., 2017). Without fletching, calibration of the spine needs to be even more controlled and the throwing technique nearly perfect. Increasing the surface area of the fletching permits to more quickly correct errors at release.

Hand-cast and Thrusting Spear

Most of the studies carried out with hand-cast spears were designed within the framework of sportive applications. These studies were mainly dedicated to understanding the influence of key parameters that would allow athletes to improve their performance in distance shooting (Gregor & Pink, 1985; Jung et al., 2012; Vassilios & Iraklis, 2013). One of the important parameters in the case of spears is the position of its center of mass. At the end of the eighties, the center of mass of sport javelins has been moved forward to reduce the distances reached by the throwers for safety reasons. The closer the position of the center of mass to the point, the more the hand-cast spear will tend to dive at the end of its trajectory. The further the center of mass from the point, the more the spear will tend to hover (Hatton, 2005). Up to now, no study has yet addressed the trajectory of thrusting spears and no data on the external ballistics of this weapon system are yet available.

Ballistic Elements Important for the Angle of Incidence

The sinusoidal rotating trajectories observed for the arrow and the dart are essential elements with regard to the question on the angle of incidence (Fig. 4). Since these projectiles fly in a conical volume and since the trajectory of their center of mass and the axis of the point are generally misaligned, they can present an angle of incidence at the moment of impact that could specifically influence the bending and compressive components of the RIS. However, even if we know that the dart presents a sinusoidal trajectory of greater magnitude than the arrow (Lepers, 2010; Whittaker, 2013), we do not know the amplitude of this sinusoid, the influence of the spine, and the effect of the trajectory on the angle of incidence for either of these two modes of propulsion. For the hand-cast spear, the position of the center of mass seems the most interesting ballistic parameter. Variations in this position prove to lead to different trajectories (diving or hovering) which potentially influence the angle of incidence. For the thrusting spear, it is not yet clear what ballistic element would be important in view of the angle of incidence.

Methods

Experimental Protocol

To evaluate the RIS of each of the four classical modes of propulsion, we designed a two-step experiment. The first step intended to document and qualify the difference (if one exists) in RIS for each standard propulsion mode was considered. In both steps, each projectile was shot 10 times at a target located at 10 m. The weapons used and their technical parameters are detailed in Table 1. The gestures and modalities of use are consistent with those used in previous experiments (see Coppe et al., 2019; Coppe & Rots, 2017).

The choices of technical parameters that we made were inspired by the ethnographic and archaeological data. For the arrows, their mass and spine needs to be adapted to the strength of the bow which shoots it (Lecaille & Menu, 1985). Therefore, we decided to use a standard arrow for our experiment, a projectile of 31 gr with a spine value that is in correspondence with the reproduction we used of the Neolithic longbow in yew of 48 lb at 29 inches of draw length. Heavier arrows than the ones we used exist in the archaeological record. For example, arrows found on the Mary Rose boat have estimated weights between 56 and 96 gr (Strickland & Hardy, 2005) for bows with estimated draw weights between 98 and 185 lb at 30 inch of draw length (Hildred, 2011). However, these bows are exceptional and most of the Neolithic bows present draw weights estimated between 35 and 70 lb (Junkmanns, 2001) which implies the use of lighter arrows. As an example, the arrows used by the Haza hunters weigh between 30 and 40 gr for bows measured between 31 and 120 lb (Pontzer et al., 2017). In modern hunting, a draw weight of 55 lb and an arrow of 30 gr is recommended (Lecaille & Menu, 1985). In view of these elements, it appears unlikely that arrows in prehistory exceeded 40–50 gr, which supports the choice of standard arrow used here.

For the darts, we used ethnographic and archaeological data as a source of inspiration. For Australian darts, Cattelain (1997) documented a variation between 145 and 460 cm in length for a weight between 250 and 624 gr and a spear-thrower varying between 50 and 200 cm. Archaeologically preserved darts and spear-throwers like the ones from White Dog Cave (Arizona, USA), have a mean length of 152 cm for darts and a spear-thrower length varying between 38 and 66 cm (Pettigrew & Garnett, 2015). The darts are relatively thin and are estimated to be lighter than

Table 1 Experimental details of 4 standard projectiles and their mode of propulsion used during the first step of the experiment

Name	Length (cm)	Spine (mm)	Center of mass in cm (%) (of length from the point)	weight (gr)
Arrow 1 (standard)	83	13	34.8 (42%)	31.12
Dart 1 (standard)	208	44.5	91 (44%)	169
Throwing spear	210	/	94 (45%)	670
Thrusting spear	210	/	/	/

Australian models (reproduction of 85 gr in Whittaker et al., 2017). Therefore, we decided to use a hazelnut dart of 169 gr as standard dart for our experiment in combination with a spear-thrower of 60 cm.

For the spears, the standard we used for throwing and thrusting follows the parameters of the wooden spears found at Schöningen (Schoch et al., 2015; Thieme, 1997).

The second phase of the experiment focused on the effect of the spine on the RIS in the case of the bow and the spear-thrower. The goal was to evaluate whether this parameter influenced the projectile trajectory to an extent that modifies the RIS. Four arrows and four darts with variables spines were used and each of them was shot 10 times. The spine of the arrows was measured with a spine tester following the method described in Greenland (2000, p. 35). For darts, the spine was measured in a similar way but with a spine tester we designed ourselves as detailed in Coppe and Rots (2017, p. 115) (Table 2).

For both experimental phases, a cardboard target full of plastic film was used. The projectiles were filmed on two axes, first on a sagittal plane over 4.5 m of their trajectory with a Photron FASTCAM NOVA S12 at 8000 frames per second (fps) and next on a frontal plane over 2 m with a Sony RX100mIV camera at 500 fps (Fig. 5). Both cameras were placed as parallel as possible to their respective plane to avoid deformations associated with parallax problems.

Measuring the Angle of Incidence

All films were subsequently analyzed with Photron Fastcam Viewer (PFV) This software permits annotations, points tracking, and the measurement of angles. To measure the angles, we drew the tangent of the trajectory of the center of mass and the axis of the point at the moment of impact. The intersection of these axes constitutes the angle of incidence (Fig. 6).

Theoretical Calculation of RIS

Thanks to available data for the level of KE reached by each mode of propulsion (see Coppe et al., 2019) and thanks to data obtained here for the angle of incidence,

Table 2 Physical parameters of the different projectiles used during the spine variation experiments

Name	Length (cm)	Spine (mm)	Center of mass (cm from the point)	weight (gr)
Dart 1 (standard)	208	44.5	91 (44%)	169
Dart 2 (rigid)	208	37	92.5 (44%)	157
Dart 3 (flexible)	215	145	102.5 (48%)	98
Arrow 1 (standard)	83	13	35 (42%)	31.1
Arrow 2 (rigid)	83	7.5	33 (40%)	31.5
Arrow 3 (flexible)	83	25	40 (48%)	28

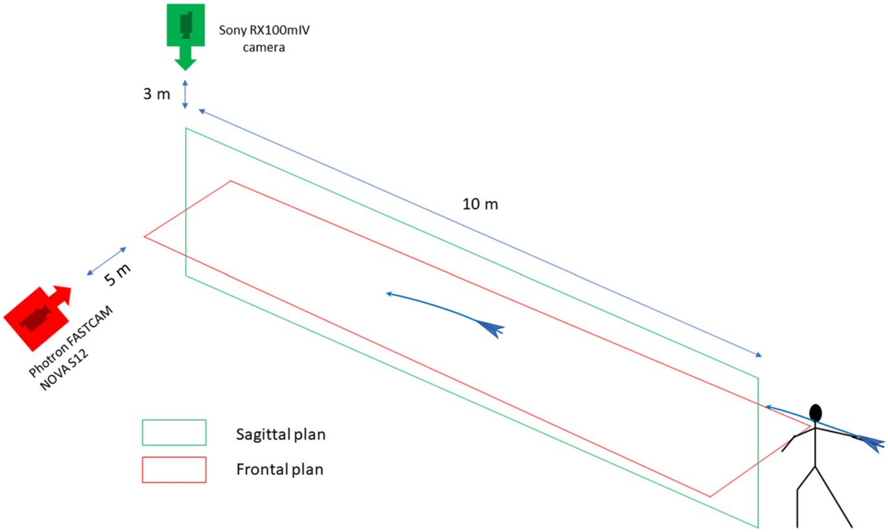

Fig. 5 Representation of the experimental setup and the sagittal and frontal planes used for the recording the trajectory of the projectile with both cameras (Sagittal: vertical camera measures side-to-side deviations; Frontal: horizontal camera measures up/down deviations)

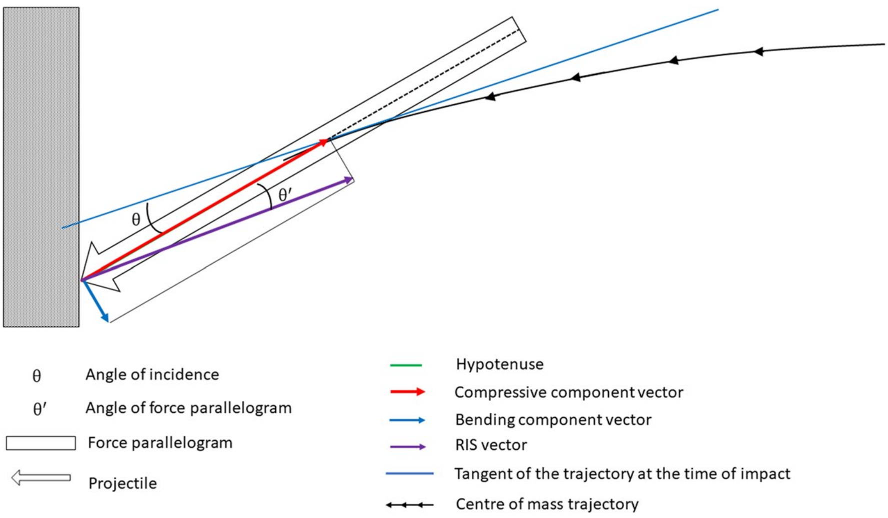

Fig. 6 Diagram that indicates how the angle of incidence is measured and with the expression of the RIS (in purple), with its component in compression (in red) and its component in bending (in blue) represented on the parallelogram of forces

it is possible to calculate the KE directed toward the compression and the bending component of the RIS for each mode of propulsion. This theoretical measurement permits a proper comparison between the different propulsion systems, but it is important that this measurement is used for a relative comparison only. Obtained values only approximate the absolute value of KE directed toward the compressive and bending component of the stress the lithic point receives upon impact because the KE of the projectile is expended in several forms during impact. One part is intended for the penetration into the target and the breakage of the elements it is composed of (skin, bones, muscles), another part dissipates in heat due to friction, another part may possibly rupture the hafting system and, finally, a part may result in the rupture of the point. Measuring the energy consumed by each of these elements is impossible and we are thus limited here to a theoretical estimation.

For the value of the angle of incidence, we use the median of the series of measured angles (in radian) obtained for each mode of propulsion. For KE we use the median of the KE values obtained for each mode of propulsion in a previous experiment with the same weapons (Coppe et al., 2019). Using median values permits to avoid the influence of extreme values as some variation in angle and KE could be observed for certain modes of propulsion.

To quantify the bending and compressive component of the RIS, we use an application of the parallelogram of forces. This physical principle allows to split the RIS into two vectors. The parallelogram of forces uses an application of the Pythagorean theorem on a right-angled triangle (Fig. 6). The plot of the parallelogram of forces is equivalent here to a right-angled triangle whose hypotenuse is the vector of the RIS and whose value is the KE of impact. The two sides of the right angle represent the bending and the compressive components that we need to calculate knowing that these stresses are perpendicular to each other. Thanks to the right-angled triangle and the measured value for the angle of incidence, we can calculate the theoretical KE directed toward both vectors (bending and compression) using the Pythagorean theorem and trigonometry (see Fig. 7). The data obtained constitute the range of theoretical KE directed toward bending and compression.

The calculation is made as follows:

Example with a KE of 72.6 J and an angle of incidence of 0.196 rad:

Calculation of bending component: $\sin 0.196 \times 72.6 = 14.14$ J
Calculation of compressive component: $\cos 0.196 \times 72.6 = 71.21$ J
Verification with the Pythagorean theorem: $71.21^2 + 14.14^2 = 72.6^2$

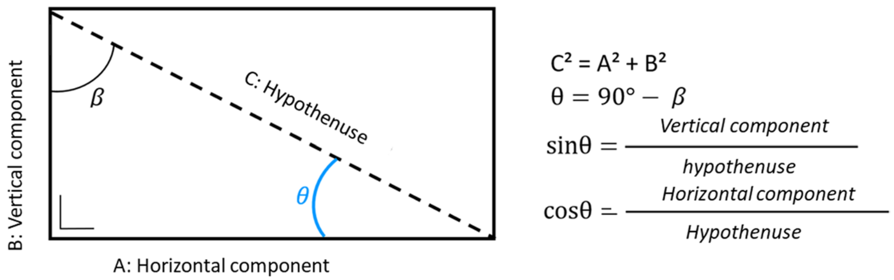

Fig. 7 Synthesis diagram of the various elements and formulas allowing the calculation of the theoretical energy of the bending (B) and the compressive (A) component of the RIS (C)

Table 3 Raw results of angle of incidence for the four standard propulsion modes

Raw data of angle of incidence in degrees										
Shots	1	2	3	4	5	6	7	8	9	10
Bow/frontal plane	2	2.5	3	2	1	2.5	2	2.5	3	2
Bow/sagittal plane	1.5	0.5	2	2	1	2	2	1.5	1.5	1.5
Spear-thrower/frontal plane	2.5	3	3.5	4	2	1	2	2,5	1.5	1.5
Spear-thrower/sagittal plane	2	1	5	4	3	2	2	2	1.5	1
Throwing spear/frontal plane	2.5	9	8.5	8.5	9.5	2	12	11.5	12	13.5
Throwing spear/sagittal plane	24	5.5	6	4	4.5	13.5	19	9	18	20
Thrusting spear/frontal plane	1.5	4	4	5.5	5.5	3	2.5	3	5	5.5
Thrusting spear/sagittal plane	5.5	3	2	5.5	6.5	7	2.5	1	2.7	4

Results

First Experimental Phase: Measuring the Angle of Incidence

The results show that important differences in angle of incidence exist between the different modes of propulsion, both in terms of the values obtained and the variation in values between shots. The bow presents the lowest values and shows the least variation, in both planes. The shots have an angle of incidence between 1 and 3° and the angle seems less developed in the sagittal plane (median = 1.5°) than in the frontal plane (median = 2.25°) (Table 3, Fig. 8). Stress in the case of such low angles of incidence is almost exclusively parallel to the axis of the tip and thus nearly exclusively oriented toward compression.

The spear-thrower has slightly higher angles of incidence varying between 1 and 5°. Both planes present similar results (sagittal/median = 2°; frontal/median = 2.25°) although a slightly higher variation is observable for the sagittal plane (Table 3,

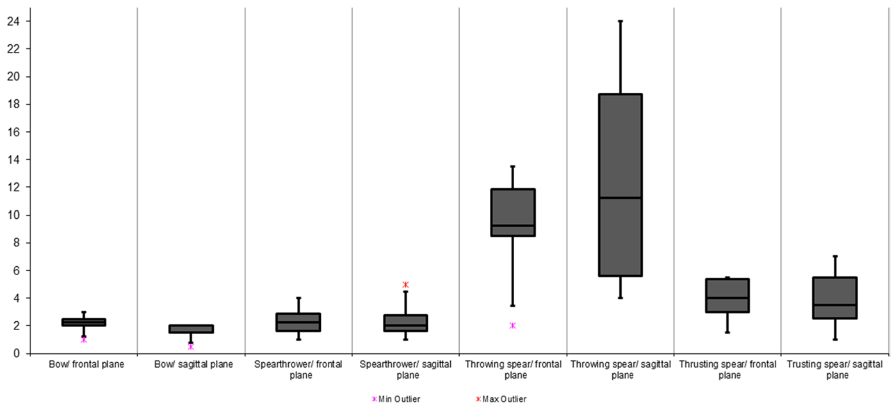

Fig. 8 Boxplot of angle of incidence for the four standard propulsion modes

Fig. 8). Stress in the case of such low angles of incidence is almost exclusively oriented parallel to the axis of the tip and thus nearly exclusively oriented toward compression even though shots presenting the highest angles of incidence (5°) are able to produce a small proportion of bending in the RIS.

The thrusting spear produces angles of incidence varying between 1 and 7° for both planes. The mean values of the angles are similar between both planes with 4° for the frontal plane and 3.5° for the sagittal plane, though the results do seem a bit more variable in the case of the sagittal plane (Table 3 and Fig. 8). A stress purely oriented toward compression is thus rare for this mode of propulsion. Most of the time, the axis of the trajectory is secant with the axis of the point thereby generating a RIS in which a small proportion is directed toward bending while the rest is oriented toward compression.

The throwing spear is the mode of propulsion that presents the highest angles of incidence, varying between 2 and 24°. The variation in the results differs between both planes: the dispersion of the results and the maximum value are higher in the sagittal plane than in the frontal plane (Table 3 and Fig. 8). Given that the angles of incidence developed by the throwing spear are important in both planes, it implies that the bending component of the stress application increases with this mode of propulsion even though the compressive component remains largely dominant.

According to previous studies, a modification in "force angle" between 5 and 15° has a notable effect on the fracture propagation (Cotterell & Kamminga, 1992: Fig. 6.10). The observed differences in terms of angles of incidence mentioned above can thus be expected to influence the propagation of fractures.

The standards we used have points of similar weight to archaeological stone points. Adding mass to the points will affect the global trajectory of the projectile. It will also affect the archer's paradox, increasing slightly the flexion of the shaft at release (Lepers, 2005). However, it should not affect the angle of incidence to any measurable degree. This was nevertheless tested for arrows and verified in a small experiment, the results of which are included in the supplementary data (available on-line). The results did not show any measurable effect on the angle of incidence of an arrow. In consequence, it should not affect a heavier projectile such as a dart or a spear.

Second Experiment: Effect of the Spine on the Angle of Incidence

Bow

To test the effect of the arrow's spine on the angle of incidence, we used three arrows presenting a different spine. The first one is the standard arrow that was also used in the previous experiment, and it presents a spine of 13 mm. The second arrow is more rigid and presents a spine of 7.5 mm and the third arrow is very flexible and presents a spine of 25 mm.

The three tested arrows prove to present relatively homogeneous values for their angles of incidence and an important overlap between arrow types. Overall, the values of the frontal plane seem lower than the ones measured for the sagittal plane (Table 4, Fig. 9).

Table 4 Measurement results of angle of incidence for the three arrows used in the spine variation experiment

Raw data of angle of incidence in degrees										
Shots	1	2	3	4	5	6	7	8	9	10
Arrow 1 (standard) frontal plane	2	2.5	3	2	1	2.5	2	2.5	3	2
Arrow 1 (standard) sagittal plane	1.5	0.5	2	2	1	2	2	1.5	1.5	1.5
Arrow 2 (rigid) frontal plane	1	1	1	3	1	1.5	2.5	0.5	1	1
Arrow 2 (rigid) sagittal plane	2	3	1.5	2	3.5	3	1.5	2	/	3.5
Arrow 3 (flexible) frontal plane	1.5	1.5	0.5	1.5	2	1.5	1	1.5	1.5	/
Arrow 3 (flexible) sagittal plane	0.5	1	1	1	1.5	2	1.5	1.5	2	1.5

The arrows have an angle of incidence between 0.5 and 3.5° (Table 4, Fig. 9) and the spine does not prove to truly affect the RIS produced by an arrow. The RIS stays almost exclusively parallel to the axis of the tip and stress is thus nearly exclusively oriented toward compression for the three tested arrows.

Spear-thrower

To test the effect of the spine on the angle of incidence for darts, we used three darts with different spine characteristics. The standard dart that was also used in the previous experiment presents a spine of 44.5 mm. In addition, a more rigid dart was used with a spine of 35 mm and a more flexible dart presenting a spine of 102 mm.

The results are more variable that for bow, and the angles of incidence prove to differ between the 3 models of darts. Even though the rigid dart does not differ so much in spine value from the standard dart, the angles of incidence obtained are higher (median at 3.5°) than for the standard dart (median at 2.5°), with also a notable increase in the variation between the shots (Table 5, Fig. 10). The more flexible

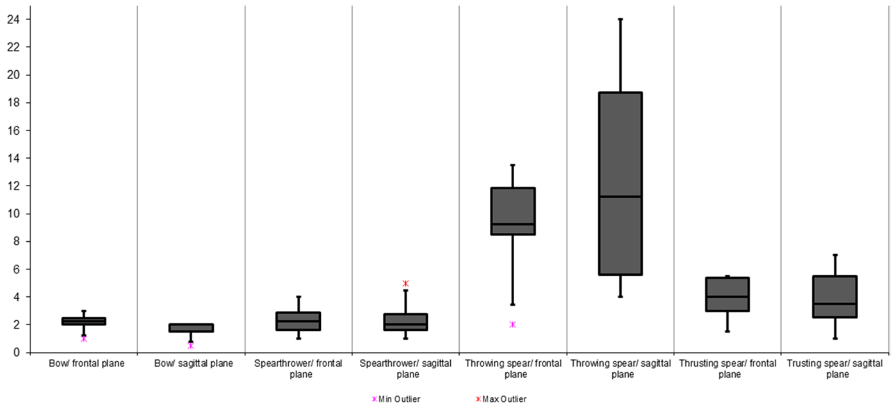

Fig. 9 Boxplot of angle of incidence for the three arrows

Table 5 Measurement results of angle of incidence for the three darts used in the spine variation experiment

Raw data of angle of incidence in degrees										
Shots	1	2	3	4	5	6	7	8	9	10
Dart 1 (standard) frontal plane	2.5	3	3.5	4	1	2	2	2.5	1.5	1.5
Dart 1 (standard) sagittal plane	2	1	5	4	3	2	2	1.5	2	1
Dart 2 (rigid) frontal plane	2,5	3	6	1	4	6	5	2	3	4
Dart 2 (rigid) sagittal plane	1	4.6	7.5	0.5	3.5	2.5	1.5	4.5	0.5	3.5
Dart 3 (flexible) frontal plane	5.5	7	5.5	6.5	5.5	3.5	8	2	2	2
Dart 3 (flexible) sagittal plane	3.5	1	5.5	9	1	9	2	8	8.5	4.5

dart produces values that differ a bit more from the standard dart. We observe an increase of the angle of incidence values (median at 5.5°) and an increase in the variation between the values (Table 5, Fig. 10).

This permits to conclude that the flexibility (spine) of the dart influences the angle of incidence upon impact, particularly when darts are too flexible. Too flexible darts tend to increase the angle of incidence and thus amplify the bending component of the impact stress, while too rigid darts remain a bit closer to what was observed for the standard dart (possibly because the spine is closer to the one for the standard dart). In the case of flexible and rigid darts, a few shots with a stress oriented toward nearly pure compression were recorded (angle of 0.5° and 1°), while this was clearly less frequent for the standard dart (see Table 5). Consequently, the spine of a dart influences the angle of incidence upon impact and thus the proportion of bending forces in the RIS. A dart with a poorly adapted spine will increase the bending component, especially when it is too flexible (Table 5 and Fig. 10).

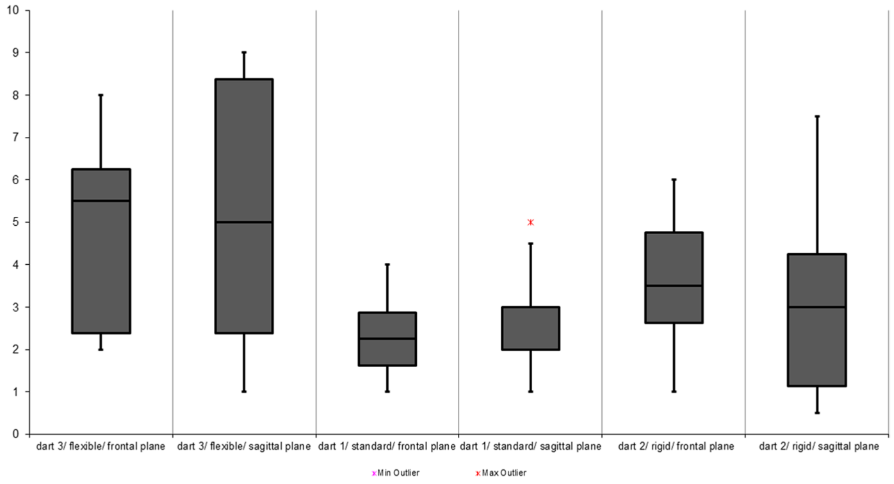

Fig. 10 Boxplot of the angle of incidence for the three darts

Kinetic Energy and the Bending and Compressive Component of RIS

We showed in the previous section that the spine does not affect an arrow's angle of incidence much. The influence is greater for darts, but the maximal median value (5.5°) obtained for darts with variable spin is still below the median value obtained for the throwing spear (11°). Therefore, a variation in spine should not much increase overlap between both weapon types. Consequently, we now focus on the calculation of the theoretical KE dedicated toward the bending or compressing component for the four standard projectiles used during this experimental program. For this calculation, we will use the maximum value for the angle of incidence independent of the plane in which it was measured (frontal or sagittal plane).

Regardless the mode of propulsion, the majority of the KE proves to be systematically oriented toward the compressive component of the RIS. However, none of the weapon systems produces an RIS that is totally oriented toward compression. A bending component is always present even though it may be very small as in the case of the bow and spear-thrower (Table 6). The bow dedicates between 1.6 (at minimum) and 4.7% (at maximum) of its KE to its bending component. The bow is the mode of propulsion which generates the lowest KE and the smallest proportion of KE oriented toward the bending component. In consequence, depending on the value considered for the angle of incidence, it produces absolute theoretical values for bending between 0.5 and 1.6 J (Tables 6, 7, 8). The spear-thrower follows the bow closely for the minimum and median value (1.7% and 3.7%) but the maximum values obtained are clearly higher than for bow with 8% of its KE oriented toward the bending component. The spear-thrower thus produces absolute theoretical values between 0.7 and 5.3 J (Tables 6, 7, 8). A clear difference is visible with the throwing spear, which dedicates between 6.6 and 31% of its KE to its bending component. The theoretical absolute values for the throwing spear are situated between 4.5 and 35.8 J that is oriented toward the bending component (Tables 6, 7, 8). The thrusting spear presents a particular case as it has lower values for the angle of incidence

Table 6 Data and results associated with the minimal angle of incidence and the resulting theoretical KE oriented toward the compressive and bending component of the RIS for the four modes of propulsion considered

	Bow	Spear-thrower	Throwing spear	Thrusting spear
Minimum KE (J)	29.6	40.6	63.9	2461.1
Minimum θ (degree)	1	1	4	1.5
Minimum θ (radian)	0.0174	0.0174	0.07	0.026
Theoretical KE oriented toward compressive component (J)	29.59	40.59	63.74	2461.1
Theoretical KE oriented toward bending component (J)	0.5	0.7	4.5	64
Proportion KE oriented toward compressive component (%)	98.4%	98.3%	93.4%	97.5%
Proportion KE oriented toward compressive component (%)	1.6%	1.7%	6.6%	2.5%

Table 7 Data and results associated with the median value for the angle of incidence and the resulting theoretical KE oriented toward the compressive and bending component of the RIS for the four modes of propulsion

	Bow	Spear-thrower	Throwing spear	Thrusting spear
Median KE (J)	30.98	51.7	72.6	2964.6
Median θ (degree)	2.25	2.25	11.25	4
Median θ (radian)	0.039	0.039	0.196	0.07
Theoretical KE oriented toward compressive component (J)	30.95	51.64	71.2	2957.3
Theoretical KE oriented toward bending component (J)	1.2	2	14.1	207.3
Proportion KE oriented toward compressive component (%)	96.3%	96.3	83.5%	93.5%
Proportion KE oriented toward compressive component (%)	3.7%	3.7%	16.5%	6.5%

Table 8 Data and results associated to the maximum angle of incidence and the resulting theoretical KE oriented toward the compressive and bending component of the RIS for the four modes of propulsion

	Bow	Spear-thrower	Throwing spear	Thrusting spear
Maximum Ec (J)	32.7	61.5	87.8	3355.9
Maximum θ (degree)	3	5	24	7
Maximum θ (radian)	0.05	0.087	0.42	0.12
Theoretical KE oriented toward compressive component (J)	32.65	61.3	80.2	3331.8
Theoretical KE oriented toward bending component (J)	1.6	5.3	35.8	401.7
Proportion KE oriented toward compressive component (%)	95.3%	92%	69%	89.2%
Proportion KE oriented toward compressive component (%)	4.7%	8%	31%	10.8%

than the throwing spear, which would correlate with a weaker bending component. This weapon dedicates between 2.5 and 10.8% of its KE to its bending component, but given that the kinetic energy of a thrusting spear is very high, it generates a very important absolute theoretical KE dedicated toward the bending component with values in between 64 and 402 J. The thrusting spear is thus the propulsion mode with the highest absolute theoretical KE expended in the bending component (Tables 6, 7, 8). However, the throwing spear still dedicates a more important proportion of its KE to the bending component in comparison to the thrusting spear (*i.e.*, between 6.6 and 31% for the throwing spear; between 2.5 and 10.8% for the thrusting spear).

These values indicate clear differences between the propulsion modes and a clear tendency for throwing and thrusting spears to favor the bending component of their RIS.

Discussion

Projectile studies have focused a lot on adequate identification of stone projectile points in the archaeological record through replicative experimentation. Several of these efforts have also resulted in some observations with regard to possible differences between propulsion modes. Fischer et al., for instance, shot arrows and hand-cast spears at animal targets and found that "*some of the spear points show bending fractures which, as far as number and size are concerned, are larger than the fractures seen on the arrowheads*"(Fischer et al. 1984: p. 24). Cattelain and Perpere (1993) shot arrows and darts equipped with Gravette flint points in similar experimental conditions. They found that the fractures are generally longer on arrow points, while dart impacts produce fractures that are shorter but more frequent and result in more fragments (Cattelain and Perpere 1993: 26). Experiments by the TFPS (*Technologie fonctionelle des pointes à cran solutréennes*) group showed that width-wide bending fractures occurred predominantly on points hafted on longer shafts (*i.e.*, not arrows) being caused by the sway of a long shaft at the end of a point stuck into the carcass, acting as a lever arm, and were thus indicative of another propulsion mode than the bow (Rots & Plisson, 2014). Petillon (2006) suggested the same explanation after finding that, on antler fork-based points, impact fractures at the base (at the level of the fork) occurred with spear-thrower shots and not with the bow, all other experimental conditions being equal. In spite of these relevant observations, it has proven difficult to propose a robust method for reliable distinctions between propulsion modes. This mainly stems from the high number of variables that are into play in the case of projectiles, our poor understanding of the interaction between these variables and the relative importance of each variable, and our lack of understanding of how these variables affect fracture patterns on stone tools. Given the complexity of the issue, a more structured stepwise approach is needed in which the influence of individual variables on the ballistic behavior of each weapon type and on the fracture phenomenon upon impact is better understood. Next to the kinetic energy dealt with in a previous study (Coppe et al., 2019), the angle of incidence is one of these key variables and an improved understanding of its effect is a crucial subsequent step in the design of a more robust method for distinguishing between propulsion modes.

On the basis of a two-phase experiment in which the angle of incidence was measured and the effect of the spine was considered, we evaluated whether the four modes of propulsion typically considered for the Paleolithic period showed a reproducible and mutually distinct RIS. The combination of data acquired in the above experiments and the KE values of each weapon system obtained in previous experiments (Coppe et al., 2019) permitted us to calculate the proportion of KE oriented toward the bending and the compressive component of the stress generated by each mode of propulsion.

Results show that all projectiles present a RIS in which the compressive component is predominant. The bending component is present for all four weapons, but its proportion depends on the weapon system. The bending component is very small for the bow, while it is slightly higher for the spear-thrower with a more important increase if the dart used has an inappropriate spine (especially when it is too flexible). The bending component is definitely important in the case of the throwing spear. The thrusting spear takes a special position in having a smaller relative component of energy expended in the bending component than the throwing spear, but given its very high KE values it has the highest absolute energy value expended in the bending component.

Assuring that a significant difference exists between the RIS produced by the bow and by the spear-thrower is complex. Both weapons definitely produce a bending component in their RIS. However, their values are very close and show a certain overlap, but their maximum values are clearly distinct (maximum for bow: 1.6 J/4.7%; maximum for spear-thrower: 5.3 J/8%). As a consequence, one may question the implication of this difference and whether 1.6 J of stress directed toward the bending component suffices to generate a bending break on all armature morphologies. It is evident that the cross-section of the point and its raw material play a crucial role here. The effect of the difference in theoretical KE developed in the bending component for each weapon system could help us to find proxies for the identification of the propulsion mode.

As demonstrated before, the angle of incidence of the different weapon systems is an important parameter. Aside from permitting the calculation of a theoretical value for the KE dedicated toward the bending and the compressive component of an impact phenomenon, the RIS also reveals the direction in which the stress is applied to the lithic armature. The more the angle of incidence is acute, the more the energy of the RIS will dissipate in the axis of the armature and, consequently, will translate itself into a strong compressive component. When the angle of incidence is less acute (*e.g.*, throwing spear), the majority of the stress is not oriented toward the body of the armature and will thus be dissipated out of the piece implying that the compressive component independent of its KE value cannot express itself in the fracture pattern of the armature. The bow is the propulsion mode which presents the acutest angle of incidence, and consequently, it is the propulsion mode that favors most the compressive component in the RIS. This important result permits to reconsider propositions made by other researchers on the interpretative potential of impact fractures on stone points. Indeed, it has been suggested that the length of impact fractures could potentially prove relevant for inferences on the propulsion mode, but this could not yet be established nor were satisfactory explanations provided of why this would be the case.

Clarkson (2016) reported experimental results leading him to suggest that the longest impact fractures are possibly caused by the use of the spear-thrower or bow, which he explains on the basis of their higher estimated KE in comparison to hand-cast and thrusting spears. In the meantime, we have shown that throwing and thrusting spears in fact develop more KE than the bow and spear-thrower (Coppe et al., 2019) and that the KE can thus not explain the results obtained by Clarkson. In the light of the new data presented in this study, we propose that the experimental results of Clarkson regarding impact fracture length are likely explained by the particular RIS linked with each weapon system instead of by the KE level only. On the grounds that the compressive component in the RIS is most pronounced for the bow and the spear-thrower, it can be argued that these two weapon systems have the highest chance to produce the longest impact fractures. Indeed, if most impact energy is dissipated in the direction of the axis of the point, even a relatively limited KE—as in the case of spear-throwers and bows—may produce long fracture negatives (Fig. 11).

Iovita et al. (2014) already reported the importance of angles in the formation of impact fractures. Indeed, they explored the effect of the angle of impact (*i.e.*, not angle of incidence) and KE on the size of impact fractures. They concluded that an increase of KE upon impact will increase fracture size but only when the projectile hits the target at 90°. If we translate this to our study, it implies that a 90° impact would result in an angle of incidence of 0° and thus a RIS that is completely oriented to its compressive component with all the KE dissipated in the axis of the point. They further specified that this relation completely disappears (or even inverts) when the impact is not at 90°. Our results permit to explain this pattern as a more important angle of incidence produces a RIS with a secant direction compared to the axis of the point and consequently, only a part of the KE will be dissipated in the compressive component of the RIS while the remainder will be dissipated in the bending component. A combined bending and compressive component will alter the size and characteristics of the impact fractures in comparison with an exclusively compressive RIS and this permits to explain the pattern observed by Iovita et al., (2014).

In spite of the fact that the study of Iovita et al. (2014) illustrates the importance of angles for understanding fracture creation in the case of an impact phenomenon and demonstrates no direct link between fracture length and a specific KE (if the angle is not taken into account), the measure of fracture length of what has been termed "diagnostic impact fractures" or "DIF" (see Coppe & Rots, 2017 for detailed discussion) has gained in popularity over the last years. While no reliable grounds exist, fracture length has been directly linked to the use of a particular propulsion mode. More specifically, fracture length has been the key argument for advocating that the bow was used in the EUP of Japan (Sano, 2016) and that the bow or spear-thrower was used in the Uluzzian of *Grotta del Cavallo* (southern Italy) (Sano et al.,

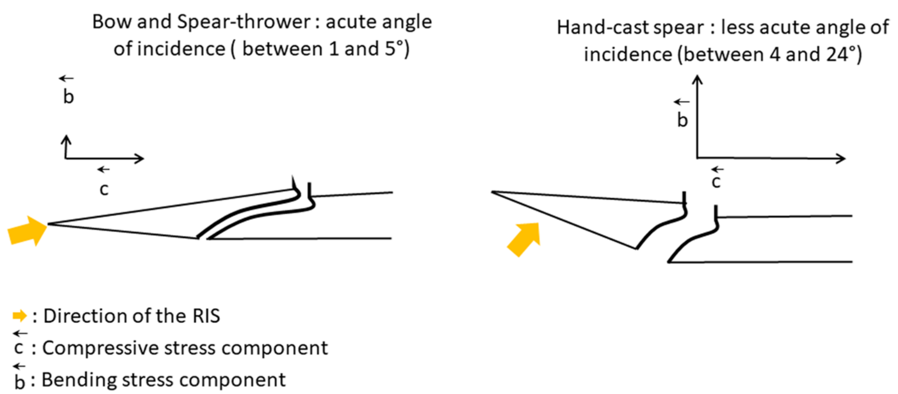

Fig. 11 Sagittal view of a breakage with different lengths of its propagation path due to two different values for the angle of incidence

2019). Previous results already demonstrated that the KE values used in those studies for each weapon system are incorrect (see Coppe et al., 2019). In addition, the results we present here falsify the direct link between impact fracture length and the KE of a propulsion mode. Indeed, the theoretical KE that is available to affect fracture length is the KE of the compressive component of the RIS only and this value depends on the total KE developed by the weapon system *and* on the angle of incidence generated by the propulsion system. Consequently, the length of impact fractures is not a suitable means on its own to try and identify a propulsion mode. It could potentially become a useful tool if one would use the theoretical KE dedicated to the compressive component instead of the total KE of a projectile impact, but this still requires to be further tested through experimentation before the interpretative potential of fracture length can be truly established.

Our results on the RIS of the different modes of propulsion also open the door to another approach. We demonstrated that the RIS is distinct between the four modes of propulsion considered, but the bow showed an interesting pattern as it proves to have an RIS (nearly) exclusively oriented toward compression. This fact is essential for future attempts to identify this propulsion mode archaeologically. If the RIS proves to sufficiently influence the creation and morphology of impact fractures as seems to be indicated by fundamental work on fracture mechanics in brittle solids (Bertouille, 1989; Cotterell & Kamminga, 1987; Tsirk, 2014), it should be possible on the basis of a sufficiently large sample of points to evaluate whether the RIS at the origin of the fracturing phenomenon was exclusively oriented toward compression or whether a (more or less important) bending component was present. This hypothesis should be further explored experimentally and could as such constitute a new approach to identify weapon systems on archaeological samples. Before this becomes reality, experiments need to test how exactly the differing proportions of bending and compressive components of the RIS generated by the different modes of propulsion interact with other variables (raw material, point morphology, resilience of the target, …) in the creation and accumulation of impact fractures. Considering the specificities of the bow's RIS as revealed in this study, we believe that this weapon system is the perfect candidate to further test this hypothesis.

Conclusion

Trying to identify weapon systems archaeologically has been an important challenge over the last few decades and in spite of what some titles of recent publications may lead to suggest, it is a challenge that has not yet been resolved. The popularity of the topic may be explained by its importance for understanding technological evolution in general and the evolution in weapon systems more in particular, but also given its key role for adequately understanding prehistoric subsistence strategies. The development of a reliable approach is thus an important enterprise that requires continued methodological efforts, and we believe that the solution lies within the integration of several fields, more in particular use-wear analysis, fracture mechanics in brittle solids, and ballistics. In this paper, we qualified the RIS of four weapon systems, identified the importance of the proportion of bending and compressive forces, and showed its potential for distinguishing between weapon systems. We demonstrated that the bow is a weapon with an RIS that is almost exclusively oriented toward compression. These results shed a new light on approaches that have been previously used to try and identify weapon systems archaeologically, such as through measuring the length of DIFs. We showed that the latter approach holds important problems and limitations and requires thorough re-evaluation. We present an alternative approach that appears to hold a lot of potential, in particular for identifying the use of the bow archaeologically. We conclude that while a reliable method for recognizing past propulsion modes is not yet established, we progressively move forward in identifying the key building blocks of such a method. We were able to demonstrate that the angle of incidence of a projectile impact, next to kinetic energy, is one of these key building blocks.

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Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by JC and CL. The first draft of the manuscript was written by JC and the direction of the study was performed by VR. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability All the data used for the study is included in the text.

Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Conflicts of Interest The authors declare no competing interests.

References

Bell, S. (2012). *A dictionary of forensic science*. Oxford University Press.

Bergman, C. A., McEwen, E., & Miller, R. (1988). Experimental archery: Projectile velocities and comparison of bow performances. *Antiquity, 62*(237), 658–670. https://doi.org/10.1017/S0003598X00075050

Bertouille, H. (1989). Théories physiques et mathématiques de la taille des outils préhistoriques. Cahiers du Quaternaire 15. Paris: Éditions du CNRS

Bleed, P. (1986). The optimal design of hunting weapons: Maintainability or reliability. *American Antiquity, 51*(4), 737–747.

Carrère, P., & Lepetz, S. (1988). *Etude de la Dynamique des Pointes de Projectiles: Elaboration d'une Méthode*. Universite de Paris I.
Cattelain, P. (1989). Un crochet de propulseur solutréen de la grotte de Combe-Saunière 1 (Dordogne). *Bulletin De La Société Préhistorique Française, 86*(7), 213–216. https://doi.org/10.3406/bspf.1989.9386
Cattelain P. (1997)− Hunting during the Upper Paleolithic: Bow, spearthrower, or both?, In H. Knecht (Ed.), Projectile technology (Springer U., pp. 213–240)
Cattelain, P. (2005). Propulseurs magdaléniens: Marqueurs culturels régionaux? *Mémoires De La Société Préhistorique Française, 39*, 301–317.
Clarkson, C. (2016). Testing archaeological approaches to determining past projectile delivery systems using ethnographic and experimental data. In Radu Iovita & K. Sano (Eds.), *Multidisciplinary Approaches to the Study of Stone Age Weaponry* (pp. 189–202). Springer.
Coppe, J., & Rots, V. (2017). Focus on the target. The importance of a transparent fracture terminology for understanding projectile points and projecting modes. *Journal of Archaeological Science: Reports, 12*, 1–15. https://doi.org/10.1016/j.jasrep.2017.01.010
Coppe, J., Lepers, C., Clarenne, V., Delaunois, E., Pirlot, M., & Rots, V. (2019). Ballistic study tackles kinetic energy values of palaeolithic weaponry. *Archaeometry, 61*(4), 933–956. https://doi.org/10.1111/arcm.12452
Cotterell, B., & Kamminga, J. (1979). The mechanics of flaking. In *Lithic use-wear analysis: proceedings, Conference on Lithic Use Wear; Burnaby, 1977.03.16–20. (Proceedings of the Conference on Lithic Use Wear; 1).* (Academic P., pp. 97–112).
Cotterell, B., & Kamminga, J. (1986). Finials on stone flakes. *Journal of Archaeological Science, 13*, 451–461.
Cotterell, B., & Kamminga, J. (1987). The formation of flakes. *American Antiquity, 52*(4), 675–708.
Cotterell, B., & Kamminga, J. (1992). *The Mechanics of Pre-Industrial Technology*. Cambridge University Press.
Dong, S., Cai, X., Wang, G., Gao, Y., & Lu, J. (2015). Numerical simulations of semi-armor-piercing warhead penetrating aircraft carrier target. In E. Sciences (Ed.), *MATEC Web of Conferences* (31,10003). https://doi.org/10.1051/matecconf/20153110003
Ellis, C. J. (1997). Factors influencing the use of stone projectile tips. In H. Knecht (Ed.), *Projectile technology* (pp. 37–74). Springer U.
English, F. (1930). The exterior ballistics of the arrow. *Journal of the Franklin Institute., 210*, 805–819.
Geneste, J., & Plisson, H. (1990). Technologie fonctionnelle des pointes à cran solutréennes: l'apport des nouvelles données de la grotte de Combe Saunière (Dordogne). *Feuilles de pierre Les industries à pointes foliacées du Paléolithique supérieur européen. Liège: Université de Liège, 293–320.* (E.R.A.U.L. 42).
Greaves, R. (1997). Hunting and multifunctional use of bows and arrows. In H. Knecht (Ed.), *Projectile technology* (pp. 287–320). Springer.
Greenland, H. (2000). *Guide Pratique pour les Archers Traditionnels*. (A. Hörnig, Ed.). ludwigshafen
Gregor, R. J., & Pink, M. (1985). Biomechanical analysis of a world record javelin throw: A case study. *International Journal of Sport Biomechanics, 1*(1), 73–77.
Hatton, L. (2005). *The physics and mathematics of javelin throwing*. Retrived 9 Novembre 2021, from https://www.leshatton.org/Documents/jav2005a_paper.pdf
Hare, P. G., Thomas, C. D., Topper, T. N., & Gotthardt, R. M. (2012). The archaeology of yukon ice patches: New artifacts, observations, and insights. *Arctic*, 65, 118–135. http://www.jstor.org/stable/41638613
Hildred, A. (Ed.). (2011). *Weapons of Warre: the armaments of the Mary Rose*. Mary Rose Trust.
Hayden, B. (Ed.). (1979). Lithic use-wear analysis. *Studies in archaeology* (p. 413). New York.
Hutchings, K. W., & Bruchert, L. W. (1997). Spearthrower performance: Ethnographic and experimental research. *Antiquity, 71*(274), 890–897.
Hutchings, W. K. (2011). Measuring use-related fracture velocity in lithic armatures to identify spears, javelins, darts, and arrows. *Journal of Archaeological Science, 38*(7), 1737–1746. https://doi.org/10.1016/j.jas.2011.03.005
Hutchings, W. K. (2015). Finding the Paleoindian spearthrower: Quantitative evidence for mechanically-assisted propulsion of lithic armatures during the North American Paleoindian Period. *Journal of Archaeological Science, 55*, 34–41. https://doi.org/10.1016/j.jas.2014.12.019
Iovita, R., Schönekeß, H., Gaudzinski-Windheuser, S., & Jäger, F. (2016). Identifying weapon delivery systems using macrofracture analysis and fracture propagation velocity: A controlled experiment.

In Radu Iovita & K. Sano (Eds.), *Multidisciplinary Approaches to the Study of Stone Age Weaponry* (pp. 13–27). Springer.

Iovita, R., Schönekeß, H., Gaudzinski-Windheuser, S., & Jäger, F. (2014). Projectile impact fractures and launching mechanisms: Results of a controlled ballistic experiment using replica Levallois points. *Journal of Archaeological Science, 48*(1), 73–83. https://doi.org/10.1016/j.jas.2013.01.031

Jung, J.-H., Kim, D.-S., Kang, H.-Y., Chae, W.-S., Yoon, C.-J., & Lee, H.-S. (2012). Kinematic analysis of the women's javelin throw at the IAAF World Championships, Daegu 2011. *30th Annual Conference of Biomechanics in Sports*, (75), 41–44

Junkmanns, J. (2001). Arc et flèche: fabrication et utilisation au Néolithique. Musée Schwab

Junkmanns, J. (2013). *Pfeil und Bogen in Westeuropa. Von der Altsteinzeit bis zum Mittelalter*. *PhD dissertation, Eberhard Karls Universität Tübingen*. ludwigshafen

Klopsteg, P. E. (1943). Physics of bows and arrows. *American Journal of Physics, 11*(4), 175–192. https://doi.org/10.1119/1.1990474

Kooi, B. W. (1998). The Archer's paradox and modelling, a Review. *History of Technology, 137*(1998), 125–137.

Lee, R. (1968). What hunters do for a living, or, how to make out on scarce resources. In Lee R. (Ed.), *Man the hunter* (Aldine, Chicago, pp. 30–48.)

Lecaille, J.-M., & Menu, J.-P. (1985). *Chasse a l'arc* (Gerfaut Cl.). Paris

Lepers, C. (2005). Arcs et flèches : histoire et savoir-faire. Bulletin de la société royale belge d'étude géologiques et archéologiques - *Les Chercheurs de la Wallonie*, *Hors série (1)*

Lepers, C. (2010). Réflexions sur l'usage du propusleur. *Bulletin Des Chercheurs De La Wallonie, 49*, 105–131.

Lepers, C. (2016). Peut-on « faire flèche de tout bois » sous prétexte d'expérimentation balistique ? *Bulletin des Chercheurs de la Wallonie*, *LII*, 79–103

Lepers, C., & Rots, V. (2020). The important role of bow choice and arrow fletching in projectile experimentation. A ballistic approach. *Journal of Archaeological Science: Reports*, *34*. https://doi.org/10.1016/j.jasrep.2020.102613

Milks, A., Champion, S., Cowper, E., Pope, M., & Carr, D. (2016). Early spears as thrusting weapons: Isolating force and impact velocities in human performance trials. *Journal of Archaeological Science: Reports, 10*, 191–203. https://doi.org/10.1016/j.jasrep.2016.09.005

Movius, H. L. (1950). A wooden spear of third interglacial age from Lower Saxony. *Southwestern Journal of Anthropology, 6*(2), 139–142. https://doi.org/10.2307/3628638

Oakley, K. P., Andrews, P., Keeley, L. H., & Desmond, J. C. (1977). A reappraisal of the Clacton spearpoint. *Proceedings of the Prehistoric Society, 43*, 13–30. https://doi.org/10.1017/S0079497X00010343

Pargeter, J., Shea, J., & Utting, B. (2016). Quartz backed tools as arrowheads and hand-cast spearheads: Hunting experiments and macro-fracture analysis. *Journal of Archaeological Science, 73*, 145–157. https://doi.org/10.1016/J.JAS.2016.08.001

Paul Clinci, C., Cristian Scurtu, I., Tarabuta, O., Ichimoaei, G., & Partene, C. (2019). Study on armour-piercing discarding sabot performance in 100 mm naval artillery. In *Journal of Physics: Conference Series* (Vol. 1297, p. 12034). IOP Publishing. https://doi.org/10.1088/1742-6596/1297/1/012034

Pettigrew, D. B. (2015). *The Ballistics of Archaic North American Atlatls and Darts*. MA thesis, Department of Anthropology, University of Arkansas, Fayetteville

Pettigrew, D., Whittaker, J., Garnett, J., & Hashman, P. (2015). How atlatl darts behave: Beveled points and the relevance of controlled experiments. *American Antiquity, 80*(3), 590–601.

Pettigrew, D., & Garnett, J. (2015). Atlatls and Darts of White Dog Cave. *Arizona. the Atlatl, 28*(2), 1–5.

Pontzer, H., Raichlen, D. A., Basdeo, T., Harris, J. A., Mabulla, A. Z. P., & Wood, B. M. (2017). Mechanics of archery among Hadza hunter-gatherers. *Journal of Archaeological Science: Reports, 16*, 57–64. https://doi.org/10.1016/J.JASREP.2017.09.025

Rots, V., & Plisson, H. (2014). Projectiles and the abuse of the use-wear method in a search for impact. *Journal of Archaeological Science, 48*, 154–165. https://doi.org/10.1016/j.jas.2013.10.027

Rust, A. Institut (1943). *Die ait-und mittelsteinzeitlichen Funde von Stellmoor*, Neumûnster, K. Wachholtz Verlag.

Sachers, J. H. (2009). Mesolithic Bows from Denmark and Northern Europe Retrieved Novembre 9, 2021, from https://www.academia.edu/11765815/Mesolithic_Bows_from_Denmark_and_Northern_Europe

Sahle, Y., Hutchings, W. K., Braun, D. R., Sealy, J. C., Morgan, L. E., Negash, A., & Atnafu, B. (2013). Earliest stone-tipped projectiles from the Ethiopian rift date to >279,000 years ago. *PloS one*, *8*(11). https://doi.org/10.1371/journal.pone.0078092

Sano, K. (2016). Evidence for the use of the bow-and-arrow technology by the first modern humans in the Japanese islands. *Journal of Archaeological Science: Reports, 10*, 130–141. https://doi.org/10.1016/j.jasrep.2016.09.007

Sano, K., Arrighi, S., Stani, C., Aureli, D., Boschin, F., Fiore, I., et al. (2019). The earliest evidence for mechanically delivered projectile weapons in Europe. *Nature Ecology and Evolution, 3*(10), 1409–1414. https://doi.org/10.1038/s41559-019-0990-3

Sano, K., & Oba, M. (2014). Projectile experimentation for identifying hunting methods with replicas of upper palaeolithic weaponry from japan. In J. Marreiros, N. Bicho, & J. G. Bao (Eds.), *International Conference on Use-Wear Analysis: Use-Wear 2012* (pp. 466–478). Cambridge Scholars Publishing.

Sano, K., & Oba, M. (2015). Backed point experiments for identifying mechanically-delivered armatures. *Journal of Archaeological Science, 63*, 13–23. https://doi.org/10.1016/j.jas.2015.08.005

Schmitt, D., Churchill, S. E., & Hylander, W. L. (2003). Experimental evidence concerning spear use in Neandertals and early modern humans. *Journal of Archaeological Science, 30*(1), 103–114. https://doi.org/10.1006/jasc.2001.0814

Schoch, W. H., Bigga, G., Böhner, U., Richter, P., & Terberger, T. (2015). New insights on the wooden weapons from the Paleolithic site of Schöningen. *Journal of Human Evolution, 89*, 214–225.

Shea, J. J., & Sisk, M. L. (2010). Complex projectile technology and Homo sapiens dispersal into Western Eurasia. *PaleoAnthropology*, 100–122. https://doi.org/10.4207/PA.2010.ART36

Strickland, M., & Hardy, R. (2005). *The great warbow : From Hastings to the Mary Rose*. Sutton Pub

Thieme, H. (1997). Lower Palaeolithic hunting spears from Germany. *Nature*. https://doi.org/10.1038/385807a0

Tsirk, A. (2014). *Fractures in knapping*. Archaeopress Publishing Ltd

Vassilios, P., & Iraklis, K. A. (2013). Kinematics of the delivery phase and release parameters of top female javelin throwers./Kinematični Parametri Faze Meta in Izmeta Pri Vrhunskih Metalkah Kopja. *Kinesiologia Slovenica*, *19*(1): 32–43

Waguespack, N. M., Surovell, T. A., Denoyer, A., Dallow, A., Savage, A., Hyneman, J., & Tapster, D. (2009). Making a point: Wood- versus stone-tipped projectiles. *Antiquity, 83*(321), 786–800.

Whittaker, J. (2013). Comparing atlatls and bows: Accuracy and learning curve, ethnoarchaeology. *Ethnoarchaeology, 5*(2), 100–111. https://doi.org/10.1179/1944289013Z.0000000009

Whittaker, J. (2016). Levers, not springs: How a spearthrower works and why it matters. In *Multidisciplinary approaches to the study of Stone Age weaponry* (pp. 65–74). Springer, Dordrecht. https://doi.org/10.1007/978-94-017-7602-8_5

Whittaker, J., Pettigrew, D., & Grohsmeyer, R. (2017). Atlatl dart velocity: Accurate measurements and implications for Paleoindian and archaic archaeology. *PaleoAmerica, 3*(2), 161–181. https://doi.org/10.1080/20555563.2017.1301133

Wood, J., & Fitzhugh, B. (2018). Wound ballistics: The prey specific implications of penetrating trauma injuries from osseous, flaked stone, and composite inset microblade projectiles during the Pleistocene/Holocene transition, Alaska U.S.A. *Journal of Archaeological Science*. https://doi.org/10.1016/j.jas.2017.10.006

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