Does Point Size Matter? How Morphometric Arguments Impact Evolutionary Models of Paleolithic Weaponry

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ABSTRACT

The invention of long-range weaponry was a pivotal technological change with significant implications for Paleolithic subsistence strategies, and it is assumed to have been a crucial factor in facilitating the spread of anatomically modern humans while migrating out of Africa. Over the last years, a prevailing hypothesis seems to have emerged that long-range weaponry appeared somewhere at the end of the Middle Stone Age and dispersed over the rest of the world together with modern humans. However, organic finds of long-range weapon components have a far more recent date, and the early appearance model relies primarily on morphometric analyses of the stone points. Metrics such as tip cross-sectional area (TCSA) and tip cross-sectional perimeter (TCSP) are argued to be reliable proxies for inferring the penetration capacity of points and the diameter of the shaft and have been used to hypothesize the use of a particular weapon system. Despite the popularity of TCSA/TCSP in projectile studies, the validity of using morphometric values to infer a particular weapon system remains insufficiently explored through experimental approaches. We use the results of a comprehensive multiparameter shooting experiment to assess the reliability of using TCSA/TCSP values as proxies for weapon technology. Our results indicate that the TCSA/TCSP value of a point does not correlate with its penetration depth, the latter being influenced more by other morphological parameters, the hafting system, and propulsion mode. Additionally, we show that small points, often interpreted as arrow tips, can effectively function with larger shafts across different propulsion modes, thereby disproving that small points could serve as a proxy for the use of arrows. Our findings raise important concerns regarding the reliability of the arguments put forward to support an early appearance of long-distance weaponry. To address weapon systems, we encourage an approach that draws more from use-wear studies and sequential experimental programs, as it permits developing finer-grained models for the emergence of long-range weapon systems.

INTRODUCTION

Long-range weaponry is a significant technological invention that impacted Paleolithic subsistence strategies and that may have been critical to the successful spread of anatomically modern humans (Marean 2005; Shea and Sisk 2010). Understanding the origin and the development process of this invention and how it affected the lives of Paleolithic hunter-gatherer populations is indeed a crucial though challenging topic to address. Most components of Paleolithic weaponry are made from organic materials, which decay over time, and the durable lithic or organic components are the primary source of information for their reconstruction. A lot of attention has therefore been devoted to the characteristics of the stone points and to possible traces of impact to evaluate whether these points could have functioned in a projectile system (Barton and Bergman 1982; Bergman and Newcomer 1983; Dockall 1997; Frison 1974, 1989; Fischer et al. 1984; Plisson and Beyries 1998; Shea 1988; Witthoft, 1968). Over the last 20 years or so, attention has gradually shifted to inferences on

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the propulsion mode, and the use of long-range weaponry especially has received an increasingly prominent role in broader discussions on the origins of modern human behaviors (McBrearty and Brooks 2000). A review of the literature gives the impression that a consensus would have emerged around an early appearance of long-range weaponry, generally situated in Sub-Saharan Africa during the Middle Stone Age, more precisely during MIS 4 (Brooks et al. 2006; Lombard 2021; McBrearty and Brooks 2000; Sisk and Shea 2011) and consequently much earlier than any organic remains of such weaponry (Becker 1945; Cattelain 2018; Junkmanns 2013; Meadows et al. 2018; Rust 1943). An important argument for this early appearance model relies on stone point morphometrics and the assumption that the stone point size closely relates to the size of the shafts, which permits inferring the propulsion mode. Indeed, authors have argued that some points identified as projectiles are so small that their use as arrow tips is the most probable hypothesis (Lombard 2011; Metz et al. 2023), that "thick points have to be mounted in thick shafts" ((Shea 2009: 194) or that the width of the points implies that an association with arrows seems the only viable hypothesis (Hays and Surmely 2005). This relation between point size and shaft size (and therefore propulsion mode) was formalized within an approach that relies on metric values only, more specifically measurements of the tip cross-sectional area (TCSA) and tip cross-sectional perimeter (TCSP) of the stone point (hereafter called the TCSA approach). TCSA/TCSP values, originally introduced by Hughes (1998) and popularized by Shea (2006), are now commonly found in the literature and serve to support most hypotheses on the early appearance of long-range weaponry.

Given the significant increase in popularity of TCSA/TCSP values over the past decade, a careful and comprehensive evaluation of their reliability for formulating hypotheses on the propulsion mode would be beneficial to the research community. After all, the strength of the model that proposes an early appearance of long-range weaponry depends directly on the reliability of the underlying data. The hypothesized relation between stone point, shaft size, and propulsion mode has been explored in relatively few studies with conflicting conclusions (Clarkson 2016; Grady and Churchill 2023; Pettigrew et al. 2023; Sitton et al. 2020).

In this article, we examine the reliability of using the stone point size to infer the shaft size and consequently the propulsion mode on the basis of a large-scale multiparameter shooting experiment. We evaluate the robustness of the data generated using TCSA values and reflect on how this affects the current model that proposes the emergence of long-range weaponry in Sub-Saharan Africa during MIS 4. We acknowledge the importance of developing broader models on the evolution of Paleolithic weaponry and we do not necessarily challenge the fact that long-range weaponry may have appeared early nor that such weaponry played a pivotal role for early modern humans, but we question whether the currently used data are sufficiently sound to validate such a model.

BACKGROUND

THE ROLE OF POINT SIZE IN CONSTRUCTING KNOWLEDGE ON LONG-RANGE WEAPONRY AND ITS EMERGENCE

Research on Paleolithic weaponry and its evolution cannot be disconnected from broader reflections on the evolution of human behaviors and the emergence of complex cognition. Indeed, several important technological innovations have been considered as archaeological proxies for the ability of long-term planning and complex cognition (McBrearty and Brooks 2000; Wadley 2013), including hafting (e.g., Ambrose 2001; Barham 2013), glue recipes (Wadley 2010; Wadley et al. 2009), ornaments (Bouzouggar et al. 2007; d'Errico et al. 2005; Vanhaeren and d'Errico 2011), art (Henshilwood et al. 2002; 2009; 2011; Texier et al. 2010; 2013), and also projectile technology (Coolidge and Wynn 2016, 2016; Coolidge et al. 2016; Lombard and Haidle 2012; Shea 2006, 2009; Shea and Sisk 2010; Sisk and Shea 2011; Wynn and Coolidge 2011; Wynn et al. 2021)(for a synthesis, see McBrearty and Brooks 2000; Scerri and Will 2023). Over the last few decades, several of the traits initially assumed to be exclusive to modern humans have also been observed among Neanderthals, such as hafting (Rots 2013), including the use of glue (Koller et al. 2001; Mazza et al. 2006), ornaments and art (for a synthesis, see García-Diez, 2022). With regard to hunting, some researchers have proposed that subsistence strategies among modern humans are distinctive from those of Neanderthals (Marean 2005) but this has been contested (Rendu 2022). Indeed, growing evidence indicates a diversity of practices among Neanderthals, including selective hunting (Gaudzinski 1996, 2006) and the exploitation of a wide range of species, both small (Blasco et al. 2022; Gaudzinski-Windheuser et al. 2023b) and large (Gaudzinski-Windheuser et al. 2023a) depending on the context and progressively blurs presumed differences in hunting behaviors between Neanderthals and modern humans (Villa and Roebroeks 2014). As a result, more emphasis is placed on the distinctive traits that potentially remain (Scerri and Will 2023). Long-range weaponry is one of those remaining traits that is still considered to be restricted to modern humans and the appearance of this innovative technology is believed to have been a game changer for the dispersal of modern humans out of Africa (Marean 2005; Shea and Sisk 2010; Sisk and Shea 2011). Long-range weapons are assumed to reduce risk in hunting, to facilitate the broadening of human diets, and to optimize energy-cost ratios (Marean 2005; Sisk and Shea 2011). A social dimension has also been proposed with the adoption of the bow argued to have impacted labor division and social disparities (Grund, 2017).

Current insights in how weapon technology evolved and varied over time and space rely on data of variable reliability and precision. Direct organic evidence is the most reliable for identifying long-range weapon technology, but it only rarely preserves. The oldest organic evidence consists of the numerous Magdalenian spear-thrower hooks made from osseous material found in France and Spain of which the oldest examples date to around 20 ka cal BP (Cattelain 2018). Possibly older hooks were found in Le Placard and Combe-Saunière (France), both attributed to the Solutrean, but this evidence remains uncertain due to inconsistencies in the radiocarbon dating of Combe-Saunière (level 1) and the excavation conditions at Le Placard (Cattelain 2018). For the bow-and-arrow, the oldest organic evidence is the arrows of Stellmoor, which dates between 11 and 12 ka cal BP (Meadows et al. 2018; Rust 1943). We consider that functional studies of stone tools are next in line in terms of reliability and precision. For Europe, the oldest evidence for the use of long-range weaponry (i.e., spear-throwers) based on functional analyses dates to around 30 ka cal BP (Coppe et al. 2023), which is about 10 ka years older in comparison to organic remains. For the bow-and-arrow, an earlier date than the Mesolithic has long been assumed (Bergman 1993; Bergman et al. 1988; Cattelain, 1997; Geneste and Plisson 1990) and recent functional results indeed suggest that the use of bow-and-arrow may at least date to the Federmesser with armatures in an apical oblique position in the hafting system (Tomasso et al. 2021), even though robust confirmation of these results requires an expansion of the experimental work with the integration of a range of weapon systems instead of the bow alone. All other published data on weapon technology rely on different lines of evidence but point morphology and point size is most often central to the argument. For instance, the Howiesons Poort segments dated to around 72–60 ka BP in the MSA of South Africa have been proposed as possible evidence for early bow-and-arrow technology (Lombard 2011; Lombard and Phillipson 2010). Impact fractures are interpreted as the result of projectile use and the location of residues is used to argue for the apical transverse position of the segment. The inferred propulsion mode, however, relies heavily on point size with the segments being viewed as too small to support any other probable hypothesis than their use as arrowheads and on the argument that the segments would show broad morphological similarities with known arrowheads such as Later Stone Age (LSA) arrowheads, microliths from the European Mesolithic, San arrowheads, and Egyptian examples with remains of their hafting system as well as preserved arrow shafts (Clark 1977; Clark et al. 1974; McBrearty and Brooks 2000). However, such morphological and size-based analogies are uncertain, and based on much more recent artifacts, and should be treated as interesting hypotheses in need of further testing and validation. Several other studies have since attempted to infer the presence of bow-and-arrow technology on similar grounds, both for the MSA of sub-Saharan Africa (Backwell et al. 2008; 2018; Bradfield et al. 2020; Brown et al. 2012; Lombard 2011; Lombard and Wadley 2016; Lombard and Phillipson 2010; Sisk and Shea 2011) and elsewhere (Langley et al. 2020; Metz et al. 2023). Given that the Howiesons Poort segments would represent the oldest evidence for the use of bow-and-arrow, it has been hypothesized that this technology would have originated in the Middle Stone Age of South Africa (Brooks et al. 2006; Lombard and Phillipson 2010; McBrearty and Brooks 2000; Shea 2006; Sisk and Shea 2011).

As a variant on point size and morphological resemblances, also metric values such as tip-cross-sectional area and perimeter (TCSA and TCSP)(see Hughes 1998) have been used to discriminate between propulsion modes following propositions made in other studies (Hughes 1998; Shea and Sisk 2010; Sisk and Shea 2011). While the relevance of using TCSA/TCSP values for identifying propulsion modes is still being debated (Clarkson 2016; Grady and Churchill 2023; Sitton et al. 2020; Pettigrew et al. 2023), these metric values quickly gained in popularity and have been increasingly used to support hypotheses about specific weapon systems, generally without prior verification of projectile use (de la Peña et al. 2013; Lombard 2020a, 2021; Lombard and Churchill 2022; Lombard and Shea 2021; Park et. al. 2023; Riede 2010; Sahle and Lombard 2024; Serwatka 2018; Shea 2006; Sisk and Shea 2011; Villa and Lenoir 2006, 2009; Wilkins et al. 2012; Wiśniewski et al. 2022), except in some cases where projectile use is first inferred on the basis of fractures that are interpreted as being due to impact (Hardy et al. 2013; Lazuén 2012; Lee and Sano 2018; Sahle et al. 2013; Sahle and Brooks 2019; Sano 2016; Yaroshevich et al. 2021). The way in which TCSA values are used varies significantly. In some studies, TCSA values are used to infer the suitability of certain artifacts to have been used as weapon armatures (Sahle and Brooks 2019; Sahle et al. 2013). In other studies, the values are used for hypotheses on both projectile use and the weapon system (Lombard 2021; Shea 2006), and in a third group of studies, TCSA values are only used to propose hypotheses on the propulsion mode, with projectile use being argued for on the basis of impact fractures (Metz et al. 2023; Sano 2016; Sano et al. 2019; Yaroshevich et al. 2021). In addition to these specific archaeological case studies (Metz et al. 2023; Sano 2016; Sano et al. 2019; Yaroshevich et al. 2021), TCSA values have also been used for modelling the emergence of long-range weapons on broad geographical and temporal scales (Hughes 1998; Lombard 2020a, 2021, 2021; Lombard and Churchill 2022; Lombard and Shea 2021; Park et al. 2023; Sahle and Lombard 2024a; Shea 2006; Shea and Sisk 2010; Sisk and Shea 2011).

Current models based on point size and TCSA/TCSP values hypothesize that the appearance of long-range weapons and, more specifically, bow-and-arrow technology significantly predates the oldest organic evidence and this for several areas. Bow-and-arrow technology has been argued to exist around 72–60 ka years ago for South Africa (Backwell et al. 2008; 2018; Lombard 2011, 2020b; Lombard and Phillipson 2010;), around 100–80 ka years ago for Ethiopia (Sahle and Brooks 2019), around 54 ka years ago for France (Metz et al. 2023) and around 48 ka years ago for Sri Lanka (Langley et al. 2020). Long-range weaponry in general (bow or spear-thrower) is also argued to exist around 50 ka years ago in the Levant (Yaroshevich et al. 2021), around 40–45 ka years ago in Italy (Sano et al. 2019) and around 35–32 ka years ago in Japan (Sano 2016). In all cases, researchers argue that bow-and-arrow technology arrived with modern humans as proposed by Shea and Sisk

(2010) who postulated that long-range weaponry probably emerged somewhere in Africa between 100 and 70 ka and dispersed out of Africa with anatomically modern humans around 60–50 ka, first to the Levant and later to the rest of the world.

Given the ever more frequent use of the TCSA approach and its role for developing broader models about the evolution of projectile weaponry, a proper verification of the reliability of this morphometric approach is essential to evaluate its relevance and effectiveness for generating meaningful insights into weapon technology and to identify potential risks and misconceptions in using such an approach for hypothesis construction.

THE CONCEPT OF TCSA/TCSP

The use of point size as a proxy for detecting specific modes of propulsion originates in research on North American projectile points (Bradbury 1998; Shott 1993), where the shift from larger notched or stemmed points to smaller triangular bifaces between 1500 and 1200 BP was considered to reflect a change in weapon technology and mark the use of the bow (Blitz 1988; Christenson 1986; see Shott 1993 for an overview). This timeline has been debated, however, with some researchers arguing for an earlier appearance, possibly during the Late Archaic or even the Paleoindian period (Amick 1994; Odell 1988). The assumption that a reduction in stone point size would reflect a reduction in shaft size and thus a shift in weapon technology has been influential—large (Baker and Kidder 1937) or heavy (Fenenga 1953) points were intuitively associated with larger weapons like spears, and smaller points with lighter weapons such as the spear-thrower or bow. Efforts were subsequently invested in the search for a threshold between both with measurements being proposed like size (Christenson 1986), mass (Fenenga 1953), and width/thickness ratio at the neck of the piece (Amick 1994; Corliss 1972; Thomas 1978), but TCSA/TCSP values are no doubt the most popular ones.

Susan Hughes (1998) initially introduced the concepts of tip cross-sectional area and tip cross-sectional perimeter for stone points and proposed that these values could serve as proxies for weapon shaft size (Sisk and Shea 2011).

The TCSA is calculated following this formula

$$\frac{\text{max. Width x max. Thickness}}{2}.$$

The TCSP depends on the geometry of the section of the point. For a bifacial point, the formula is expressed as

$$4 \times \sqrt{\left(\frac{\text{Width}}{2}\right)^2 + \left(\frac{\text{Thickness}}{2}\right)^2}.$$

For a unifacial point, the formula is expressed as

$$\text{Width} + 2 \times \sqrt{\left(\frac{\text{Width}}{2}\right)^2 + \text{Thickness}^2}.$$

Two fundamental principles underlie the use of TCSA/TCSP values. The first principle is that a projectile point should be wider than its shaft so that the wound is large enough to permit effective penetration of the shaft and fatal injury through blood loss (Hughes 1998). A stone point's cross-sectional area is therefore considered indicative of the diameter of its shaft, and with each propulsion method being characterized by specific shaft dimensions, it is also considered indicative of the weapon system (Hughes 1998; Shea 2006; Sisk and Shea 2011). The second principle is that TCSA/TCSP values permit evaluation of the capacity of a point to penetrate the target (Hughes 1998). Several experiments were conducted to explore this relationship, and all results converge towards TCSP being a more accurate predictor of point penetration than TCSA (Grady and Churchill 2023; Sisk and Shea 2009; Sitton et al. 2020).

Studies that rely on TCSA/TCSP values subsequently postulate that a comparison of the TCSA/TCSP values of a given archaeological point sample with a reference sample of known propulsion mode permits one to hypothesize which weapon type would be best suited for the archaeological points (Hughes 1998; Lombard et al. 2022; Shea 2006; Sisk and Shea 2011). However, the reliability of the correlation between TCSA/TCSP values and propulsion modes has been criticized by several authors (Rots and Plisson 2014; Villa and Roebroeks 2014; see Clarkson 2016; Pettigrew et al. 2023) and has never been validated through methodological work.

THE REFERENCE FRAMEWORK THAT UNDERLIES THE TCSA/TCSP APPROACH

To build a reference framework of points with known propulsion modes, researchers have used ethnographic, archaeological, and experimental data and have tried to identify thresholds for TCSA/TCSP values to discriminate between propulsion modes. The first reference set that was used consists of the ethnographic arrows and preserved archaeological darts conserved in the American Museum of Natural History (Thomas 1978). It was originally constructed to understand the timing of the appearance of long-range weapons in North America. All stone-tipped arrows and darts that were sufficiently preserved were measured (i.e., 132 arrows from 24 tribes in North America, 10 complete or fragmented darts from different burial or cave sites in North America). Additional reference material was provided by 29 complete or fragmented darts, mostly coming from the American Southwest, even if three examples come from Australia, Alaska, and Peru, respectively (Shott 1997).

To expand the reference sample and to compensate for the absence of spears, Shea (2006) incorporated an experimental sample (n=54) that had been produced during his study of Levallois points in the Near East (i.e., Kebara Levels IX–XII, Tabun Cave Units I–II and IX, Qafzeh Cave Level XV, Hayonim Cave Level E, and Tor Faraj Rockshelter Level C (Shea 1988; Shea et al. 2001; 2002: 56). The experimental points had been hafted on spears and used with a crossbow in a shooting experiment (Shea et al. 2001; 2002) to understand the fracture patterns and to evaluate whether certain morphological parameters of the stone points would influence their effectiveness. The authors observed more catastrophic breaks on the narrower and longest points of their sample (Figure 6 in Shea et al. 2002) and concluded that long and narrow point morphologies are too fragile to be used as thrusting spear. This experimental sample, with the exception of the ones considered as too fragile to be functional, consisted of 28 points and was used to represent the ideal morphology of thrusting points. The TCSA values of these experimental points were subsequently integrated as the reference for spears within the TCSA approach (Shea 2006), which is an example of circular reasoning. There is, of course, no basis to assume that these morphologies are exclusive to thrusting spears, as the experimental set-up did not test their functionality with other propulsion modes. The reliability of the reference for thrusting spears is therefore questionable. Likewise, there are no grounds to assume that smaller points could not be used in conjunction with thrusting spears. While the experiment conducted by Shea et al. (2001; 2002) provided interesting data regarding the possible use of Levallois points as weapon implements, it did not demonstrate that Levallois points would be strictly associated with a particular mode of propulsion.

In spite of the issues raised, the above reference framework has been widely used within the TCSA/TCSP approach to interpret archaeological material from across the world (mainly Europe, Near East, Africa, but also Asia) and dating from the Middle Paleolithic and Middle Stone Age to the early Upper Paleolithic (Brooks et al. 2006; Costa 2012; Lee and Sano 2018; Shea 2006; Sahle and Brooks 2019; Sano 2016; Sano et al. 2019; Serwatka 2018; Shea and Sisk 2010; Sisk and Shea 2011; Villa and Lenoir 2006, 2009; Wilkins et al. 2012). Several researchers have since criticized the poor representativity of the reference framework with its low number of integrated pieces and its restricted coverage in terms of geography and chronology and have questioned its relevance for areas and time periods outside the Holocene of North America (see Clarkson 2016; Marsh et al. 2023; Sahle et al. 2023). Indeed, both the ethnographic record as well as more recent archaeological records of stone points with preserved shafts show that the variability in TCSA/TCSP of the points can be very high (at least for arrows and darts). Archaeological arrowheads preserved within their foreshafts and complete shafts from Holocene burial sites of South America (Marsh et al. 2023) testify to the important range in TCSA values (and thus significant overlap) compared to values reported previously (Shott 1997; Thomas 1978). Also the TCSA/TCSP values of Australian dart stone points (Kimberly points and Leilira blades) divert significantly from the values proposed by Thomas (1978) (Newman and Moore 2013). Moreover, it is noteworthy that Thomas (1978), in his first selection, excluded the ethnographic darts from the Arctic because he considered them too different to serve as a relevant comparison for North American Paleoindian points.

More recently, efforts have been invested to expand the reference collection and integrate ethnographic material from sub-Saharan Africa, thereby incorporating thrusting and throwing iron-tipped spears, as well as iron- and bone-tipped poisoned arrows (Lombard 2020b; Lombard et al. 2022; Sahle and Lombard 2024a; Sahle et al. 2023). While this development is a positive step towards an increase in representativity of the reference framework, the inclusion of raw materials other than stone presents significant challenges when the goal is to use this reference for the interpretation of stone tools. Iron, bone, and stone do not share the same mechanical properties, and the points differ in their manufacturing process and impact resistance, while also the thickness required to create a functional point varies significantly. Moreover, with the elaboration of the reference framework, the variability in point size and TCSA/TCSP values for each propulsion mode has increased significantly and overlap between threshold values is now considerable, particularly between North American darts, light throwing spears (Lombard 2021; Lombard and Shea 2021; Sahle and Brooks 2019; Sahle et al. 2023), and heavy throwing and thrusting spears (Sahle et al. 2023). With the integration of more iron-tipped projectiles (Sahle and Lombard 2024b; Sahle et al. 2023), metal points now dominate the reference framework but the implications of the differences in physical properties between metal and stone points has not yet been independently tested. It can therefore be questioned whether the current reference framework has any relevance for inferences about Paleolithic stone points. Up to now, no validation has yet been performed but the reference has nevertheless been used in multiple studies (see Lombard et al. 2022; Sahle and Lombard 2024b for examples).

MATERIAL AND METHODS

This study uses the stone points from a large-scale multi-parameter projectile experiment (Exp46) performed at TraceoLab, University of Liège, and incorporated in the reference collection TRAIL (Rots 2021). The experiment aimed to evaluate the role of point morphology, hafting strength, and propulsion mode on the creation and accumulation of fractures during projectile impact (Coppe and Rots 2025). The experiment included three stone point morphologies (triangular, bifacial, and backed points) in two size categories (small and large) to simulate the most commonly observed morphological categories of archaeological stone points. For each morphology, a specific archaeological example served as a model (Table 1) even if the intention was not to reproduce the morphological variation observed at a given site. One raw material was used (Harmignies flint from a quarry in Spiennes, Belgium) and all points were photographed before hafting. All points were measured, and TCSA/TCSP values were calculated (Figures 1 and 2; Supplementary Information 1).

Three hafting modes that vary in strength were used because it influences how stress is absorbed upon impact. Points were secured on their shafts either with glue, with sinew bindings, or with a combination of both (i.e., glue + sinew to reinforce + glue to protect the binding) (Coppe 2020; Coppe and Rots 2017). The spear shafts (throwing and thrusting) were crafted from spruce, following the parameters of the Schöningen spears (cf. Schoch et al. 2015; Thieme 1997). Darts were made from hazel, and arrows from pine. The physical characteristics of the shafts are detailed in Table 2.

TABLE 1. MORPHOLOGICAL CATEGORIES OF THE STONE POINTS USED IN THE EXPERIMENT (Exp46) AND THE ARCHAEOLOGICAL EXAMPLE USED AS INSPIRATION FOR THEIR MANUFACTURE.

Morphological group	Size	Archaeological inspiration
Backed points	Small (a)	Microgravette points (O'Farrell 1996)
	Large (b)	Gravette points (O'Farrell 1996)
Triangular points	Small (c)	Hamburgian points (Weber 2009)
	Large (d)	Levallois points (Plisson and Beyries 1998)
Bifacial points	Small (e)	Michelsberg triangular bifacial points (Manolakakis and Garmond 2011)
	Large (f)	Still Bay bifacial points (Villa et al. 2009)

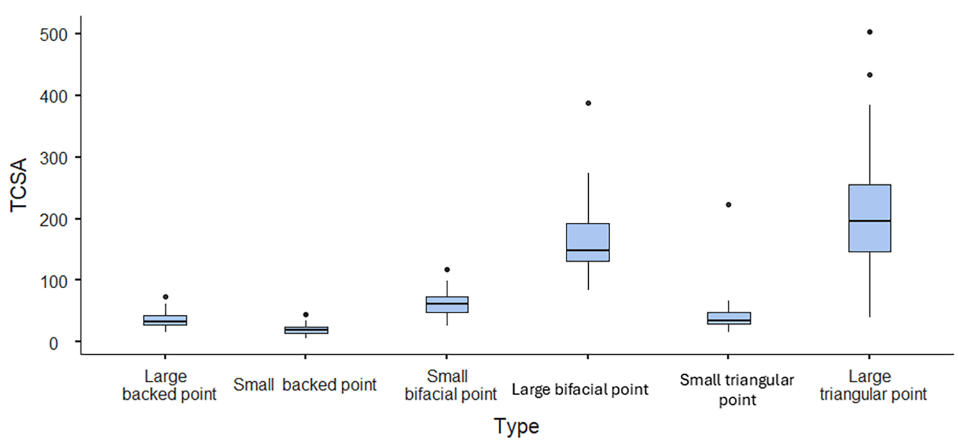

Figure 1. Boxplot of the distribution of TCSA values of the experimental points grouped by morphological category.

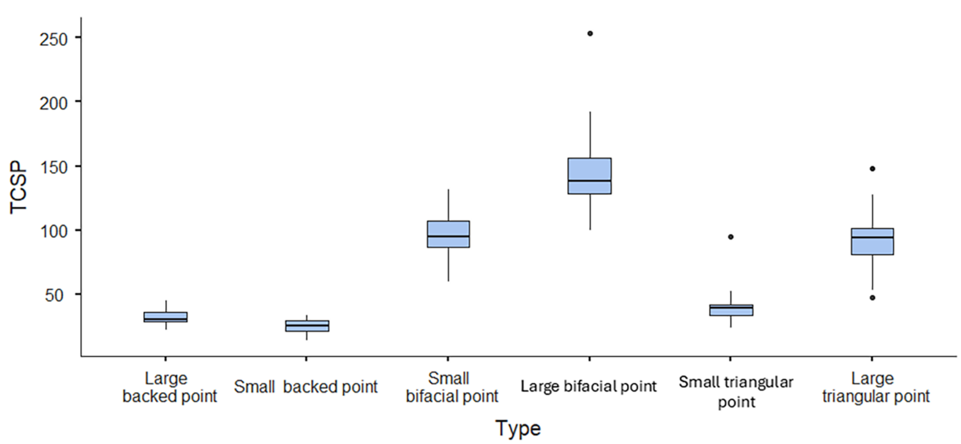

Figure 2. Boxplot of the distribution of TCSP values of the experimental points grouped by morphological category.

TABLE 2. PHYSICAL PARAMETERS OF THE SHAFTS USED IN THE EXPERIMENT (Exp46).

	Min.	Median	Max.
Arrow spine (cm)	1.1	1.2	1.5
Dart spine (cm)	3	4.6	7.2
Arrow weight (g)	45	48	59
Dart weight (g)	160	208	311
Spear weight (g)	497	600	750
Arrow length (cm)	80		
Dart length (cm)	210		
Spear length (cm)	210		
Arrow diameter at the tip (mm)	5.3	6.2	7.2
Dart diameter at the tip (mm)	10.5	11.4	11.9
Throwing spear diameter at the tip (mm)	9.6	10.2	12.5
Thrusting spear diameter at the tip (mm)	9.5	10.2	11.6
Arrow diameter at 15cm from the tip (mm)	8.5	8.5	8.5
Dart diameter at 15cm from the tip (mm)	13.4	14.5	15.5
Throwing spear diameter at 15cm from the tip (mm)	23.4	26.2	34.2
Thrusting spear diameter at 15cm from the tip (mm)	27	28.5	30.2

The four propulsion modes traditionally considered for the Paleolithic were integrated—thrusting, throwing, spear-thrower, and bow (see Coppe et al. 2019; 2022) for details on shooting techniques and gestures). Projectiles were shot by experienced shooters—for throwing and thrusting spears by JC (10–15 years of experience) and for the spear-thrower and bow by Christian Lepers (CL, TraceoLab; more than 20 years of experience). Standardized shooting distances from the target were used—10m for the bow and the spear-thrower and 5m for the throwing spear. The thrusting spear was used in close contact with the target. The target was composed of a pony skeleton refitted in anatomical position and embedded in ballistic gel (10% mixture [Fackler and Malinowski 1985; for the recipe see Jussila 2004]), subsequently covered by a rehydrated and stretched pony skin, with a thickness of 1mm to 2mm (for more details see Coppe and Rots 2017). We shot the points up to the moment that a visible fracture was created, with a maximum of 10 shots. In total, 360 projectiles were used during this program (60 for each point morphology, 90 for each propulsion mode, and 120 for each hafting mode). We systematically recorded the penetration depth achieved by the projectile for each shot.

For this study, we evaluated the impact of different variables on the penetration success. We used a reference value of 10cm to consider a penetration as successful in agreement with existing literature regarding lethal wounds. We acknowledge that the lethality of a shot also depends on the location of the wound and that hunters will aim for vital organs located in the rib cage (e.g., lungs, liver, kidney, heart, and large blood vessels [Ashby 1996; Kurzejeski et al. 1999; Mertz 2010]). For medium and large-sized prey, the vital organs are positioned at varying depths within the animal's body and for some locations, a penetration wound of 5cm through skin, fat, and muscle may already be lethal. For the largest animals (e.g., proboscideans), 12cm is said to be a minimum (cf. Kilby et al. 2022). Frison (1974) reports a lethal penetration depth of 15cm in his experiments with a *Bos taurus* (to perforate the heart). Friis-Hansen (1990) reports that 15cm of depth is required for the rib cage of a roe deer to make it fall after 10 seconds of running. Other studies seem to overestimate the necessary penetration depth and propose that 20cm is necessary for medium game (Salem and Churchill 2016; Shea et al. 2002; Tomka 2013), 25cm for large game (Sitton et al. 2020; Tomka 2013) and even 58cm for large herbivores such as bison (Tomka 2013). However, based on a general appreciation of existing literature including studies on animal anatomy we consider a depth of 10cm as a reliable threshold because this permits the perforation of vital organs located behind the ribcage for most medium to large game (e.g., cervid, horse, wild boar, bovid) and can thus be considered as fatal. The precise distance between the skin and the vital organs in the rib cage can be found for deer and wild boar in Mertz (2010) and for bovid in Pavaux (1982: Figure 116).

TABLE 3. PENETRATION DEPTHS (in mm) RECORDED FOR THE 507 SHOTS CONDUCTED DURING THE EXPERIMENT (Exp46), ORGANIZED ACORDING TO THE THREE MAIN PARAMETERS THAT WERE TESTED (propulsion mode, hafting system, and point morphology [S=sinew, G=glue, GSG=glue-sinew-glue]).

		N Shot	Minimum	Median	Mean	Maximum	SD
Mode of propulsion	Bow	124	0	13.5	12.2	24	6.7
	Spear-thrower	110	0	13.8	11.7	25	7.7
	Throwing spear	118	0	10	9.6	22	6.3
	Thrusting spear	155	0	14	16.5	66	16.1
Hafting system	S	182	0	11	11.7	56	11
	G	164	0	14	13.3	53	9.3
	GSG	161	0	13.5	13.5	66	12.2
Point morphology	Small backed point	90	0	11.5	11.9	66	9.6
	Large backed point	93	0	12.2	12.3	56	9.9
	Small triangular point	124	0	14.8	14.5	64	10.6
	Large triangular point	60	0	12.5	14.8	56	13
	Small bifacial point	65	0	13	11.8	41	10.6
	Large bifacial point	75	0	7	10.9	54	12.2

RESULTS

Eighty-three points yielded no reliable data, either because the points missed the target, impacted another material, or were lost. A total of 507 successful shots on the target were performed with the remaining 277 points and all of these shots permitted exploitation of the data on penetration depths (see Table 2). In total, 16% of the shots (N=81) failed to penetrate the skin, primarily due to the rupture of the bindings upon impact (43% of failed shots), the rebound of projectiles on the skin (41% of failed shots, mostly bifacial points), or the fracturing of the point upon contact with the target (16% of failed shots, mostly backed points). Penetration depths ranged from 0cm to 66cm, and 321 shots (63%) can be considered as lethal since their penetration exceeded 10cm in depth (Table 3).

WHAT VARIABLES INFLUENCE THE SUCCESS RATE OF PROJECTILES IN PENETRATING THE SKIN?

The skin is the first barrier that a projectile needs to cross to achieve lethal penetration. Therefore, we evaluated the influence of point morphology, hafting system, and propulsion mode on the success rate of a projectile to penetrate the skin (Figure 3) and we tested the results statistically using a Chi-square test. Point morphology emerged as a major factor (χ^2=13.3, df 5, p=0.021) with small and large bifacial points having most difficulty penetrating the 2mm pony skin compared to other point morphologies (small bifacial points: 74% success; large bifacial points: 77% success). Triangular points, both small and large, proved most successful at penetrating the skin (large triangular points: 89%

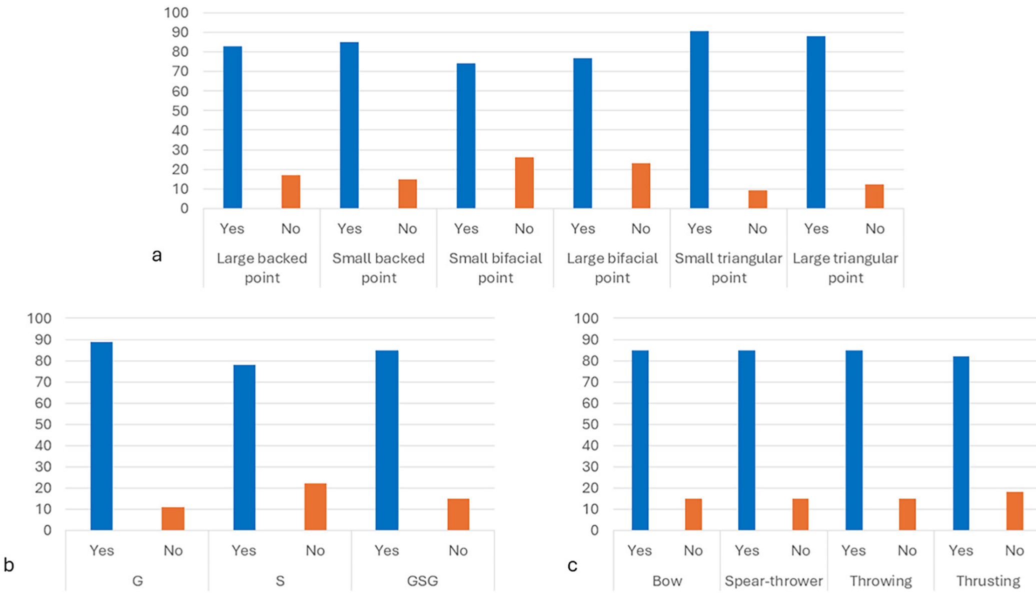

Figure 3. Success rate of the points to penetrate the skin for each point morphology (a), hafting system (b), and mode of propulsion (c). For the hafting system: G=glue, S=sinew, GSG=glue-sinew-glue.

success; small triangular points: 91% success) (see Figure 3a). Also, the hafting mode proved to significantly influence the success with which projectiles penetrated the skin (χ^2=7.51, df 2, p=0.023). Points that were simply glued to the shaft proved most successful (89% success) while points secured with sinew bindings only were least successful (78% success) (see Figure 3b). The mode of propulsion did not appear to significantly affect the success rate with which projectiles penetrated the skin (χ^2=0.735, df 3, p=0.865) (see Figure 3c).

All TCSA/TCSP values of the stone points were recorded (see Figures 1 and 2) and we observed no particular influence of these values on the penetration success. The distribution of TCSA/TCSP values is similar between the points that succeeded in penetrating the skin and those that failed (Figures 4 and 5). This was confirmed by a Mann-Whitney U test (TCSA: WMW=16184, p=0.376; TCSP: WMW=15506, p=0.148).

WHICH VARIABLES INFLUENCE THE SUCCESS RATE OF PROJECTILES IN REACHING LETHAL PENETRATION DEPTHS (10CM OR MORE)?

Each point morphology successfully reached penetration depths of 10cm or more, independent of the hafting system or propulsion mode. All projectile combinations tested here can thus deliver fatal wounds (Figure 6). However, some combinations proved more successful than others. For instance, certain point morphologies have lower success rates in achieving a lethal penetration depth when associated with a particular mode of propulsion. Examples are the small backed point combined with the throwing

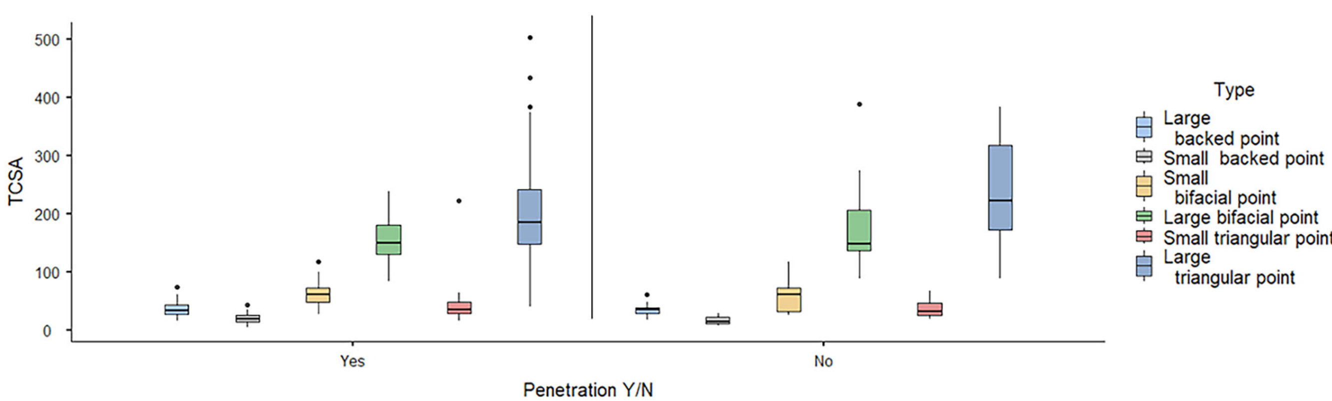

Figure 4. Boxplot of the distribution of TCSA values for the experimental points that successfully penetrated the skin and those that failed, subdivided by point morphology.

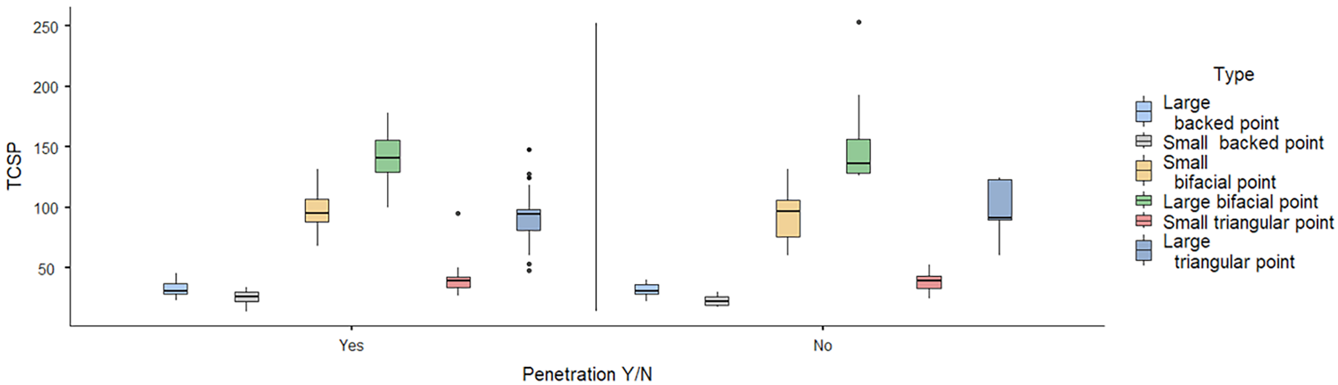

Figure 5. Boxplot of the distribution of TCSP values for the experimental points that successfully penetrated the skin and those that failed, subdivided by point morphology.

spear and the large bifacial point combined with the spear-thrower, compared to other combinations (see Figure 6).

A Chi-square test was again used to evaluate the influence of point morphology, hafting system, and propulsion mode on the success at reaching a penetration depth of 10cm or more. Only the propulsion mode proved to be significantly influential (χ^2=19.8, df=3, p<0.001). The bow and the spear-thrower proved to have very similar success rates (86% for the bow, 84% for the spear-thrower), while the throwing spear and thrusting spear proved somewhat less successful (63% and 70%, respectively) (Figure 7b). The hafting system (χ^2=0.261, df=2, p=0.878) and point morphology (χ^2=8.54, df=5, p=0.129) do not significantly influence the frequency of reaching penetrations of 10cm or more (Figure 7a, c). However, the use of the spear-thrower or the throwing spear in combination with a large bifacial point significantly decreased the success rate (56% for the spear-thrower compared to an average of 84% across morphologies; 45% for the throwing spear compared to an average of 63% across morphologies). The same goes for small backed points in combination with the throwing spear (50% success rate compared to an average of 63% across morpholo-

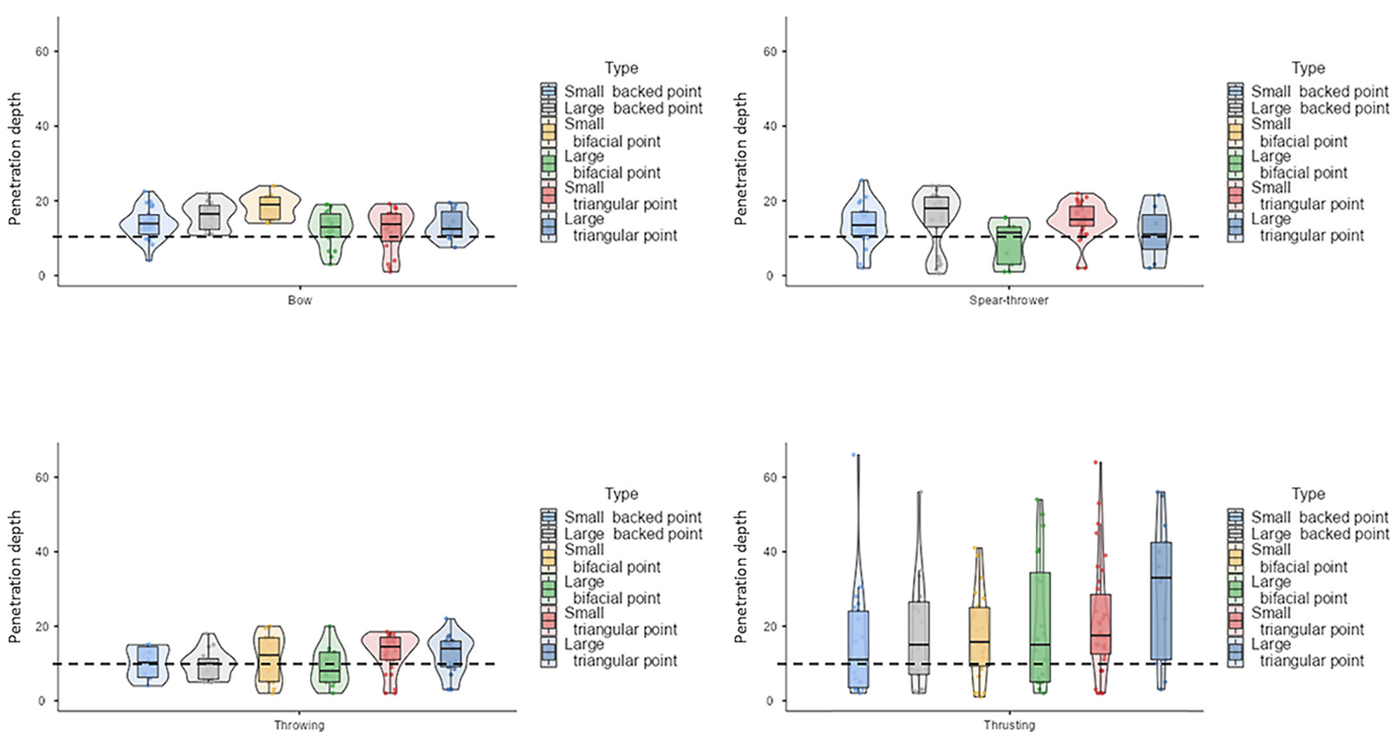

Figure 6. Violin boxplot of the range in penetration depths (cm) obtained in the experiment, subdivided by mode of propulsion. The black line marks the penetration depth required for a lethal wound in the case of medium to large game.

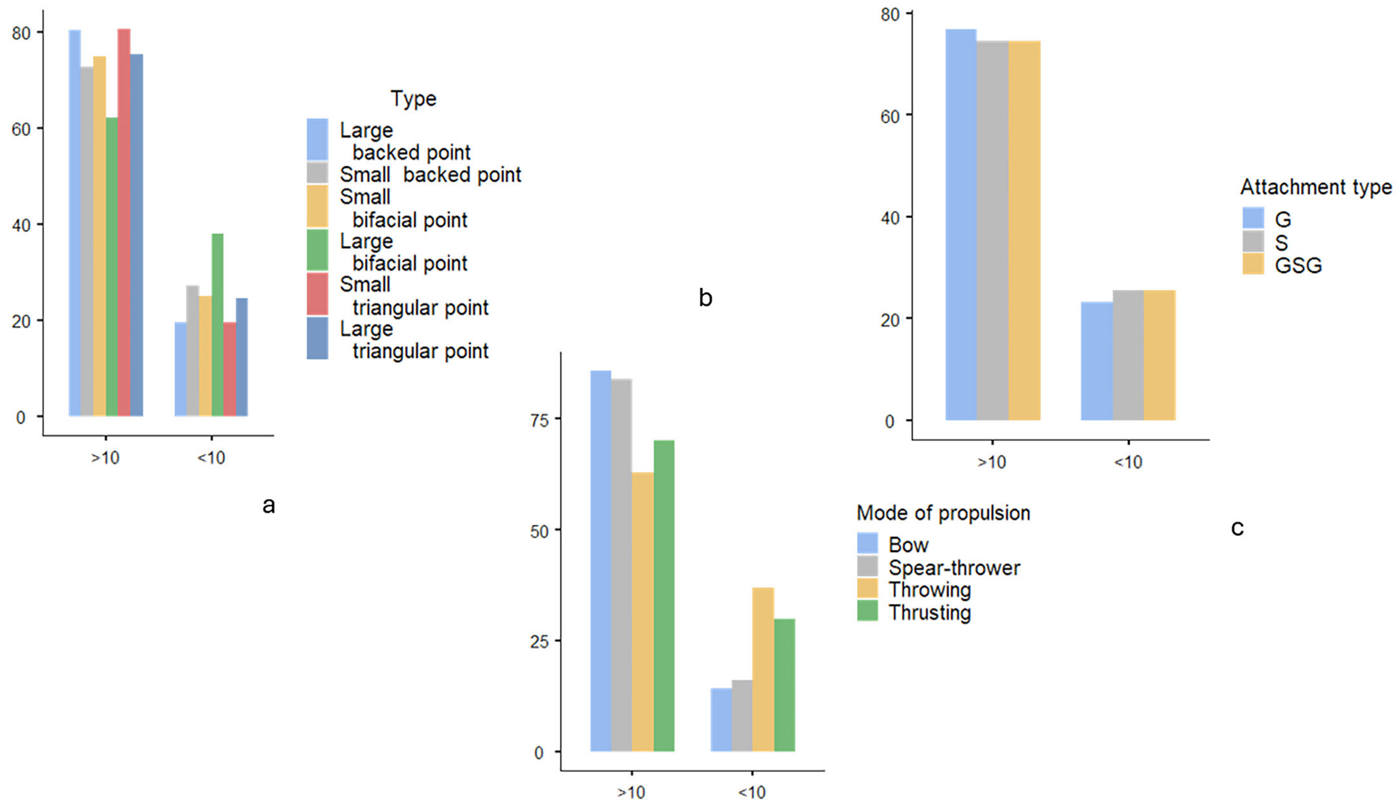

Figure 7. Proportion (%) of the shots that reached penetration depths above or below the threshold of 10cm for each point morphology (a), mode of propulsion (b), or hafting system (c). For the hafting system, G=glue, S=sinew, GSG=glue-sinew-glue.

gies) or the thrusting spear (57% success rate compared to an average of 70% across morphologies).

By contrast, TCSA/TCSP values did not prove to significantly influence success rates in reaching lethal penetration depths, as revealed by a Mann-Whitney U test (TCSA: WMW=15212, p=0.134; TCSP: WMW=15234, p=0.139). Given the low p-values, the issue was explored more in-depth, thereby separating between propulsion modes because this variable proved highly influential. The influence of TCSA/TCSP values on success rates now proved to be significant for the spear-thrower sample (TCSA: WMW=360, p=0.019; TCSP=384, p=0.036), but not for any of the other propulsion modes (Bow: TCSA: WMW=592, p=0.447; TCSP=632, p=0.697; Throwing spear: TCSA: WMW=1150, p=0.915; TCSP=1080, p=0.544; Thrusting spear: TCSA: WMW=1643, p=0.802; TCSP=1683, p=0.966).

The spear-thrower sample is thus the only one for which we observed a weak but significant negative correlation between an increase of the TCSA (Spearman's rho= -0.241, df=108, p=0.011) or TCSP (Spearman's rho= -0.247, df=108, p=0.009) of the point and a decrease of the penetration depth. We did not detect this correlation for any of the other modes of propulsion (Figure 8). Within the spear-thrower sample, we could identify that the large bifacial points were responsible for the result because these points systematically had lower penetration depths than other points shot with the spear-thrower (see Figure 6). Indeed, no significant influence of TCSA/TCSP values on the success rate of reaching penetration depths of 10cm or more can be identified once large bifacial points are removed from the sample (TCSA: WMW=292, p=0.148; TCSP=311, p=0.232).

POINT SIZE VERSUS SHAFT SIZE—DOES IT MATTER?

It is repeatedly argued in the literature that a point should be larger than its shaft to guarantee sufficiently deep penetration of the projectile into the target and thus a lethal wound by blood loss. This aligns with ideas on weapon efficiency also put forward by Hughes (1998) and it is the second fundamental principle on which the TCSA/TCSP approach relies. Because of this, small points are frequently associated with narrow shafts, leading to the hypothesis that they were used with the bow. However, the reliability of this link was never tested. Moreover, the principle seems to disregard the fact that the distal part of spears and darts (or their foreshafts) can be shaped to ensure a smooth transition between the point and the shaft. Such shaping permits accommodation of most point sizes on any shaft (see below for more details) (see Figure 13 below; Figures S1–S3).

To test the reliability of the link between point size and shaft size, we selected the smallest points from our experimental sample using a value of 10mm in width as a maximal cutoff. This choice relies on the threshold used by Metz et al. (2023) to hypothesize the use of the bow on

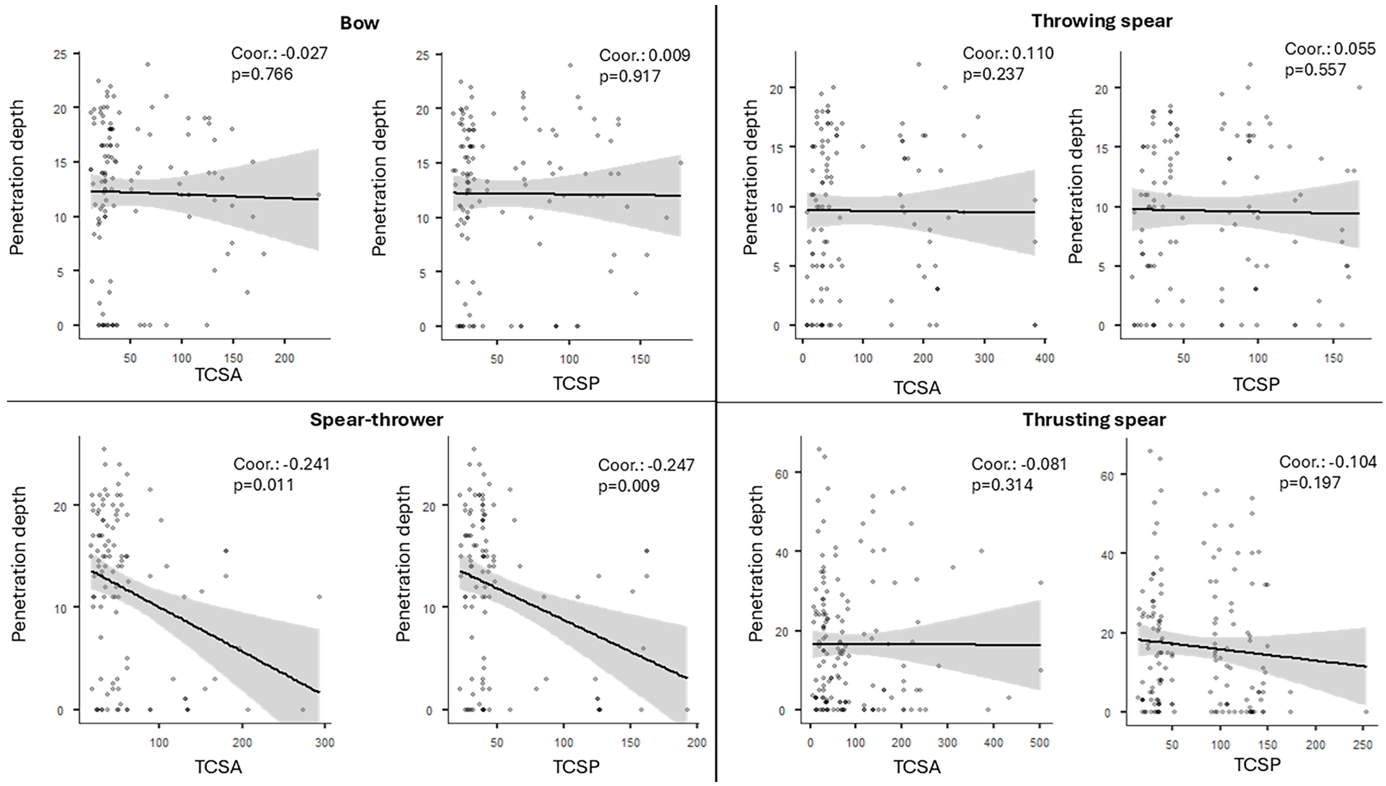

Figure 8. Correlation chart comparing penetration depth with TCSA/TCSP values of the points, organized by mode of propulsion.

the grounds that below this width, a point would be too narrow to be used with any other weapon system (Metz et al. 2023). While our experimental dataset (Exp46) was not specifically designed for this test, 36 microgravette points nevertheless meet this criterion (Tables 4 and 5).

On average, the spear points in this sample proved smaller than the dart points and arrowheads, but this is a random occurrence and not deliberate (Figures 9 and 10). We note that the range of TCSA values per weapon delivery system (see Figure 9) crosscuts ranges considered by some researchers as being ideal for poisoned (TCSA between 4–18mm^2) and unpoisoned arrow tips (TCSA between 17–47mm^2) (Lombard et al. 2022).

The selected 36 small points were used for a total of 59 shots. None of the weapon delivery systems exhibited a 100% success rate for penetrating the skin, with unsuccessful shots being as follows—four with the bow (22% of the shots), one with the spear-thrower (14% of the shots), four with the throwing spear (22% of the shots), and three with the thrusting spear (21% of the shots). Failures to penetrate the skin are associated with either the failure of the hafting system upon impact (5 out of 12), breakage of the point when hitting the target (4 out of 12), or a rebound on the skin (3 out of 12). Ranges of penetration depths were comparable between arrows and darts, 0–22.5cm and 0–21cm, respectively. The range of penetration depths for thrust-

TABLE 4. TCSA/TCSP CHARACTERISTICS OF THE 36 MICROGRAVETTES SELECTED FROM THE EXPERIMENTAL REFERENCE SET THAT RESPECT THE MAXIMAL CUTOFF OF 10MM IN WIDTH.

	TCSA (mm²)					TCSP (mm)				
	Mean	Median	S-D	Min.	Max.	Mean	Median	S-D	Min.	Max.
Bow	19.6	19.9	5.7	11.2	28.1	23.6	24.4	2.3	19.3	27.5
Spear-thrower	20.3	18	4.3	16.6	28.1	23.5	22.7	1.9	21.9	26.8
Throwing	16.2	17.2	6.7	7.6	32.8	22.1	22.9	3.5	15.9	28.4
Thrusting	15.4	12.8	7	5.3	28.9	20.9	19.2	4.7	13.9	29.5

TABLE 5. NUMBER OF POINTS AND SHOTS PER MODE OF PROPULSION.

	N Shots	N points
Bow	18	12
Spear-thrower	7	5
Throwing	18	12
Thrusting	16	7
Total	**59**	**36**

ing spears was larger, between 0–30.5 cm, while ranges obtained with throwing spears were lower, between 0–15 cm (Table 5, Figure 11), but with mean and median values that are still above the lethal threshold of 10cm. A Welch's ANOVA test indicates that the difference in penetration depths between propulsion modes is statistically significant ($F(3, 16.9)=4.29$, $p=0.020$). Further analysis using a Games-Howell post-hoc test reveals that the observed difference is caused by a significant difference in the distribution of penetration depths between the bow and the throwing spear (mean difference: 5.66, $p=0.011$) (Table 6; see Figure 11). Aside from the throwing spear reaching lower penetration depths overall, all propulsion modes proved to inflict lethal wounds when combined with small stone points, though this is less frequent for throwing spears (see Figure 11).

We also compared the distribution of penetration depths for shots with points below or above 10mm in width for the complete experimental dataset (Table 7, Figure 12). No significant differences could be identified for points propelled with the bow (Mann-Whitney U test=904, $p=0.722$) or spear-thrower (Mann-Whitney U test=344, $p=0.839$), or for thrusting spear points (Mann-Whitney U test=962, $p=0.378$). However, a significant difference was found for throwing spear points (Welch's t-test: $t(28)= -2.33$, $p=0.027$) with the larger points leading to deeper penetrations (see Table 7; see Figure 12).

These results indicate that both small (10mm in width or below) and larger stone points can be used effectively with bows, spear-throwers, and thrusting spears without significantly affecting penetration performance. However, the situation is less clear for throwing spears as a reduced penetration performance could be observed when points narrower than 10mm were used, at least when these are hafted axially in an apical position. Nevertheless, the results refute that a strict link would exist between small stone points and the use of the bow. Point size is thus not a reliable argument when trying to identify propulsion modes or when reflecting on the evolution of projectile weaponry.

DISCUSSION

The way in which stone projectile points and their propulsion mode can be identified are longstanding questions in prehistoric research. Aside from direct organic evidence and functional data, the morphometric characteristics of the stone points and in particular their TCSA/TCSP values are now commonly used to assess projectiles and/or their propulsion mode; it is here referred to as the TCSA approach. Over the years, the TCSA approach has been used to support models on both the appearance of stone-tipped weaponry (Sahle et al. 2013; Wilkins et al. 2012) and the appearance of long-distance weaponry (Backwell et al. 2008; 2018; Langley et al. 2020; Lombard 2011, 2020b, 2021; Lombard and Churchill 2022, 2022; Lombard and Phillipson 2010; Lombard and Shea 2021; Lombard and Wadley 2016; Metz et al. 2023; Sahle and Brooks 2019; Sahle and Lombard 2024b; Sano 2016; Sano et al. 2019; Sisk and Shea, 2011; Yaroshevich et al., 2021). The latter is fundamental for broader debates on the evolution of Paleolithic weaponry, but also on human evolution. After all, the use of long-distance weaponry is considered to be exclusive to modern humans and a game changer for their successful dispersal out of Africa to Asia and Europe (Shea 2009; Sisk and Shea 2011).

When addressing the identification of projectile points, such studies rely on the principle that a point's metrics

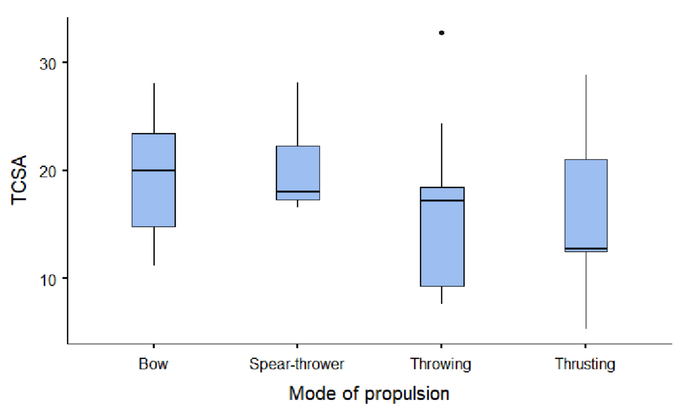

Figure 9. Boxplot showing the distribution of TCSA values by mode of propulsion for the 36 pieces that have a maximal width of 10mm.

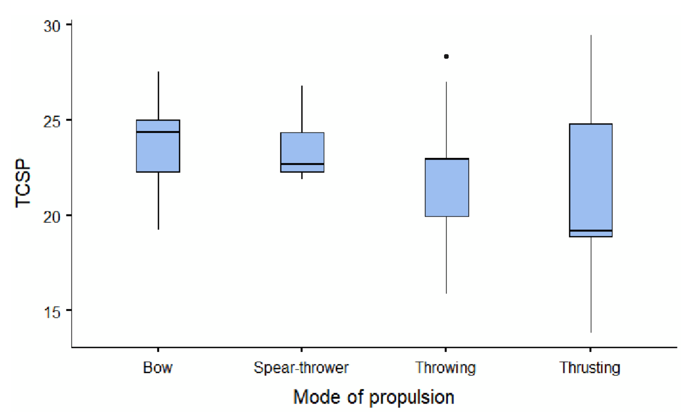

Figure 10. Boxplot showing the distribution of TCSP values by mode of propulsion for the 36 pieces that have a maximal width of 10mm.

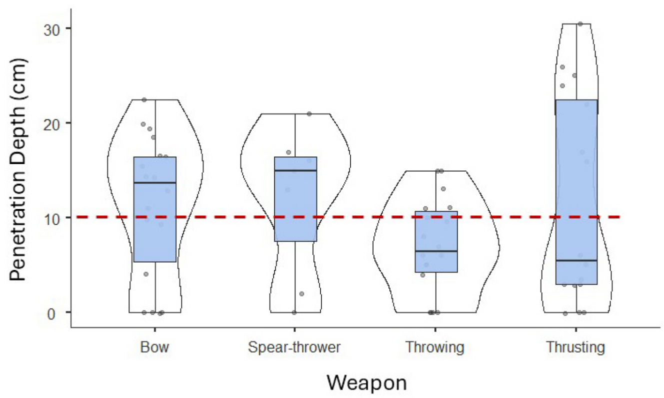

Figure 11. Boxplot of the penetration depths (cm) obtained with small points, subdivided by mode of propulsion. The red line indicates the threshold value of 10cm used in this study for lethal wounds in the case of medium-sized to large-sized game.

permit evaluation of its capacity to penetrate a target even though this does not imply that the stone point would actually have been used as a projectile. When addressing the propulsion mode, such studies rely on the principle that a point must be larger than its shaft to enable lethal penetration. As a result, a particular range of stone point sizes is correlated with what is hypothesized as being the best suitable shaft width from which the most likely propulsion mode is subsequently deduced. In this study, we aimed to test the reliability of both principles because these underlie the TCSA approach that is now commonly used in projectile studies. To do so, we used a large experimental reference collection of projectile points available at TraceoLab, University of Liège (Experiment 46 of TRAIL). The goal was to test the validity of both principles and to evaluate whether the TCSA approach can be considered a reliable means for inferences on projectile use and propulsion modes.

TABLE 6. RESULTS OF THE GAMES-HOWELL POST-HOC TEST, WHICH IDENTIFIES SIGNIFICANT DIFFERENCES IN THE DISTRIBUTION OF PENETRATION DEPTHS BETWEEN THE BOW AND THE THROWING SPEAR.

		Spear-thrower	Throwing	Thrusting
Bow	Mean difference	0.621	5.66	0.468
	P value	0.996	**0.011**	0.999
Spear-thrower	Mean difference		5.04	-0.154
	P value		0.357	1.000
Throwing	Mean difference			-5.190
	P value			0.367

TABLE 7. SUMMARY OF THE RESULTS OBTAINED FOR THE PENETRATION DEPTHS (in cm) GROUPED BY PROPULSION MODE.*

Stone point width	Propulsion mode	N Shot	Minimum	Median	Mean	Maximum	SD
<10 mm	Bow	18	0	13.7	11.4	22	7.6
	Spear-thrower	7	0	15	12	21	7.9
	Throwing spear	18	0	6.5	7	15	5
	Thrusting spear	16	0	5.5	11.5	30.5	11
>10 mm	Bow	106	0	13.5	12.3	24	6.6
	Spear-thrower	103	0	13.5	11.6	25.5	7.7
	Throwing spear	100	0	11	10.1	22	6.4
	Thrusting spear	139	0	14	17.1	66	16.5

*Results are compared between the 59 shots performed with the 36 smallest points in the sample (10mm or less in width) and the 448 shots performed with the 241 larger points (above 10mm in width).

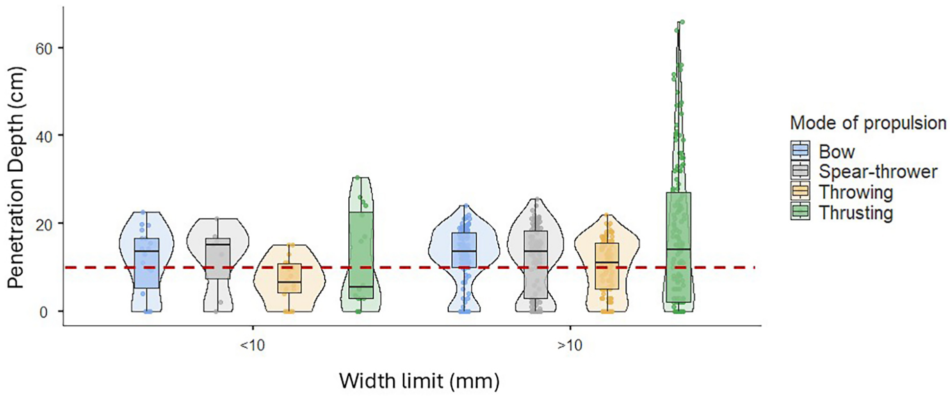

Figure 12. Boxplot comparing penetration depths (cm) of the smallest points (10mm in width or below) with those of the larger points (more than 10mm in width) from the experimental dataset (Exp46), grouped by propulsion mode. The red line marks the threshold for lethal wounds, set at 10cm in this study.

Two recent studies (i.e., Grady and Churchill 2023; Sitton et al. 2020) have tried to provide an experimental validation of the first principle (i.e., TCSA/TCSP of the stone point as a proxy for penetration capacity). They used highly controlled experimental set-ups and kept a maximum number of parameters constant. They also succeeded in controlling point morphology, which is typically difficult to do, thanks to their use of 3D-printed triangular and diamond shaped points (Grady and Churchill 2023) or lanceolate bifacial ground flint points (Sitton et al. 2020), allowing them to isolate the potential effect of TCSA/TCSP. In both studies, the authors observed an inverse relation between TCSP and projectile penetration while no relation was found between TCSA and penetration performance. In our study, we observed an inverse relation for both TCSA and TCSP but only in the case of large bifacial pieces propelled with a spear-thrower. For all other point morphologies and modes of propulsion, no relation could be observed between the TCSA/TCSP values and the penetration capacity of a point. Also Pettigrew et al. (2023) did not observe a relation between TCSA/TCSP and penetration capacity in their actualistic experiments in which multiple parameters interacted. We observed in our multifactorial study that penetration phenomena are governed by a complex interplay of different parameters, some of which have significant influence, such as stone point morphology (i.e., sharpness of the apex and edges) and mode of propulsion (i.e., energy and speed of the projectile), while others (e.g., TCSA/TCSP) have a more subtle effect that only becomes apparent when the more influential parameters are artificially controlled (cf. Grady and Churchill 2023; Sitton et al. 2020).

We demonstrated that the general morphology of the stone point and not its TCSA/TCSP values influences the projectile's capacity to penetrate the skin. For the three morphological categories of points that we used, we observed that differences in success rate are particularly marked between bifacial points (lowest success rate) and triangular points (highest success rate) while backed points had intermediate scores. To understand this pattern, we refer to the results of experimental approaches in forensic medicine (Chadwick et al. 1999; Gilchrist et al. 2008; Hainsworth et al. 2008; Nolan et al. 2013), which have shown that the most influential parameter for skin piercing is the sharpness of the point's very tip, referred to as "apex" here. The sharpness of the cutting edges also contributes, but only in a secondary way, to widen the hole once the skin is pierced (Hainsworth et al. 2008; Nolan et al. 2013). Bifacial points, while durable, have an apex that is less sharp than other point morphologies and higher lateral edge angles. Triangular points, by contrast, have a very acute apex and also very acute lateral edges (if unretouched) and therefore constitute the sharpest morphology tested in our experiments. The general morphology of a point and the sharpness of its apex and edges are therefore more important parameters to predict the penetration capacity of a point than its TCSA/TCSP.

We showed that the mode of propulsion does not directly influence a point's capacity to penetrate the skin, but influences rather its depth of penetration, including its success in reaching lethal depths. We observed a complex interaction between the kinetic energy generated by the weapon and the characteristics of the stone point. The thrusting spear is the weapon that produces the highest kinetic energy (on average 2900J; see Coppe et al. 2019) and regardless of the associated stone point, it consistently achieves the deepest penetrations. However, this relationship between kinetic energy and penetration depth is less notable with the bow, spear-thrower, and throwing spear, as their kinetic energy values are not as far apart even if they are still different (average value for bow: 28J, for spear-thrower: 44J, for throwing spear: 72J; see Coppe et al. 2019). Because of this lower kinetic energy, the importance of point morphology and especially the sharpness of the edges increases. This is why some combinations of points and propulsion modes have a lower success rate in reaching lethal penetrations, such as the throwing spear and spear-thrower combined with large bifacial points. The reduced sharpness of the apex and edges of the bifacial points explains the lower range of penetration depths, but an additional factor is speed. Indeed, we observed a notable difference when large bifacial points are used in combination with a bow compared to a spear-thrower or a throwing spear with the bow leading to deeper penetrations. This difference may seem surprising because it does not follow the logic that an increase in kinetic energy should result in greater penetration if the sharpness of the points is equal. However, the penetration capacity of an object into a soft material does not depend solely on its kinetic energy and sharpness but is also influenced by the speed of the cutting action (Atkins 2006; Goda et al. 2023; Mora 2021; Mora and Pomeau 2020; Reyssat et al. 2012). Slicing a tomato with a somewhat dull knife is a good example as we have all observed that a quick (horizontal) slicing motion is more effective than a cutting motion that applies vertical pressure (Reyssat et al. 2012). In the latter case, the complete object is deformed until the contact area ruptures but if the edge is too dull, the tomato will simply crush. Conversely, during a quick slicing motion, the material is stretched along the cutting axis and the deformation is much more localized. The faster the slicing motion, the more localized the deformation and the shearing stress will cause the material to rupture along the cutting axis, which consumes less energy than in the case of a vertical cut (Atkins 2006; Goda et al. 2023; Mora 2021; Mora and Pomeau 2020; Reyssat et al. 2012). The same phenomenon is at play when projectiles penetrate the target and explains the close interaction between the sharpness of the point, the speed of the cutting action, and the available energy. That is why large bifacial points penetrate deeper when used with the bow (average speed of an arrow: 45m/s) compared to other (slower) propulsion modes (average dart speed: 25m/s; average throwing spear speed: 14m/s) (Coppe et al. 2019). In the case of thrusting spears, the success rate is explained by the very high kinetic energy that results from the body weight of the user being implicated in the gesture. However, this does not imply that bifacial points cannot be used effectively with slower propulsion modes like spear-throwers or hand-thrown spears. Special attention to sharpening the distal tip and edges of the points is required to ensure the weapon functions optimally, as illustrated by the meticulous bifacial shaping of Kimberley points used on darts and spears by indigenous people in central and northern Australia (Elkin 1948; Newman and Moore 2013).

Consequently, due to the complex interaction of important parameters such as kinetic energy, speed, and point morphology, the potential influence of a less important parameter such as TCSA/TCSP is not visible. Therefore, TCSA/TCSP values are not reliable proxies for predicting a point's penetration capacities because the influence of these morphological parameters on the process proves too limited in comparison to other more dominant parameters.

With regard to the second principle (i.e., a point should be larger than its shaft to ensure lethal penetration) on which the TCSA approach relies for hypotheses on the projectile propulsion mode, it is true that no sudden increase in width should occur at the transition between a stone point and its shaft so as to not hinder penetration. When shafts are tapered towards the tip, points of any size can be successfully hafted and used on a broad range of shaft types. Indeed, we observed in our experiments that the smallest points in our sample function effectively on shafts of much greater width, such as darts and thrusting spears (mean dart width: 14.5mm; mean thrusting spear width: 28.5mm) (see Figure S3). An excellent illustration of this is provided by Kimberley points from Australia, which often feature a hafting area that is narrower than the glue bulge securing it (see Figure 3 in Akerman et al. 1978). In these cases, the transition between point, adhesive, and shaft does not follow the principle that the point must be wider than the shaft. Instead, effectiveness lies in the smooth and progressive transition created by the adhesive (Akerman et al. 1978). These elements therefore challenge the assumption that points of 10mm width or less are only functional when used with arrows, which call into question the evidence presented by Metz et al. (2023) for the existence of the bow at 54 ka BP. A similar case can be made for the early appearance of the bow in South Africa, as proposed by Lombard (2011). While the early appearance of the bow is theoretically possible, the size of the points is central to the current argument, and we documented that it is not a valid indication of the mode of propulsion. Interpretations based on the TCSA/TCSP approach overlook the potential offered by the use of foreshafts or distally tapered shafts. The use of foreshafts is documented with organic remains from at least the early Upper Magdalenian onwards (around 16.5–15 ka cal BP) (Pétillon 2016) and its use could have been more widespread and extended back in time. Foreshafts offer multiple advantages such as contributing to the overall equilibrium of the projectile, allowing swift replacement of the distal part in case of damage during impact, and enabling a reduction in the diameter of the distal section of the shaft when necessary. A perfect example of the use of narrow foreshafts in combination with a shaft of considerable diameter is the Roman pilum, which was employed from the 5th century BC to the early 6th century AD in a wide range of military contexts (Bishop 2017; Feugère 1993). This weapon featured shafts weighing between 200g and 1700g, with a steel foreshaft measuring between 27cm and 120cm in length and with a notably reduced diameter, which tapers the distal end of the javelin. These foreshafts were tipped with a pyramidal point measuring between 7mm and 33mm in width (Bishop 2017). Stone points of a width of 10mm or less can thus be used easily on any weapon system if foreshafts are used or when the shaft is tapered towards the point.

Moreover, the tapering of shafts also explains some of the results we obtained in our experiments, especially for throwing spears. Indeed, during the experimental set-up, we did not devote particular attention to optimizing the distal tapering of the throwing spears in order to maximize their penetration capacity, because our primary goal was to achieve a penetration of minimum 5cm in order to reach the ribs of the target. As a result, we attribute the lower success rate in reaching penetrations above the lethal threshold

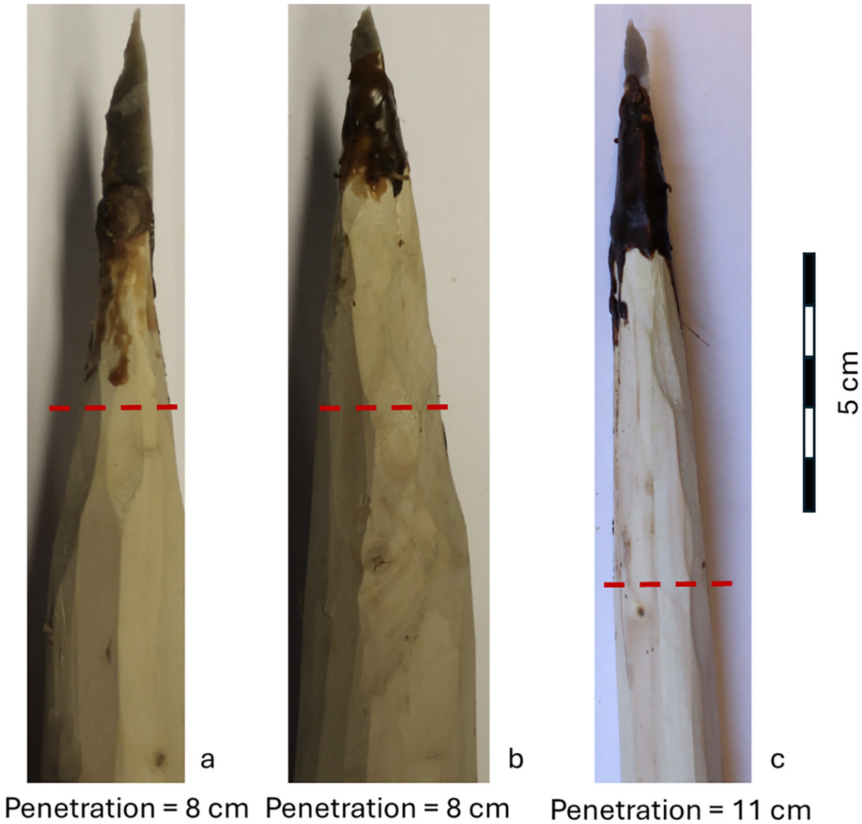

Figure 13. Three examples of throwing spears with stone points of less than 10mm in width (a: Exp46_508, b: Exp46_512, c: Exp46_264). The red line marks the penetration depth achieved by each spear during the experiment. A smooth and gradual tapering of the distal end of the shaft, as in example c, enhances penetration. The stone point does not need to be larger than the shaft to ensure lethal penetration as long as the shaft is tapered towards the point to reduce friction between the shaft and the interior of the target.

(i.e., 10cm as used in this study) with the throwing spear combined with a small-backed point to the design of the spears we used. A more pronounced tapering of the distal end of these spears when combined with small stone points would have drastically enhanced their penetration capacity (Figure 13). By contrast, such tapering is less essential for thrusting spears, as the generated kinetic energy is more than sufficient to overcome this problem and achieve lethal penetration consistently.

Small stone points can thus function perfectly on large shafts, but the opposite scenario also is documented with very large points being effectively used in combination with narrow shafts. Examples are the very large points used with arrows by the Inuit of northwest Alaska (Witthoft 1968), or the macroblades and large Kimberley points used with narrow dart shafts among the indigenous peoples of central and northern Australia (Newman and Moore 2013). In our experiments, we also hafted large triangular points (Levallois points) (see Figure S1) and large bifacial points (Still Bay points) onto arrows (on split shafts) (see Figure S2), as well as small backed points (microgravettes) onto throwing and thrusting spears (see Figure S3). The only limitation we encountered was the thickness of the stone point relative to the shaft. A point is never too small to be hafted onto a split shaft, but some points can be too thick for certain arrow shaft. Points that are more than 4mm thicker than the shaft's diameter could not be securely hafted with our hafting system, which set the maximal thickness of the arrowpoints on 12.5mm in our experiments. The diameter of the arrow shaft is directly related to the draw strength of the bow (Klopsteg 1943). We used a bow with a draw strength of 48 pounds at 30 inches and the arrow shafts therefore measured 8.5mm in diameter. It seems unlikely that Paleolithic arrowpoints hafted onto split shafts could have exceeded 14mm in thickness. The thickest arrow shafts found in an archaeological context are currently those from the Mary Rose, an English warship that sank in 1545 AD. The bows recovered from the ship had draw strengths of 150–160 pounds at 30 inches, which is well beyond what can be expected for Paleolithic bows, and the associated arrow shafts had diameters between 11mm and 13mm (Alexzandra 2011). Neolithic bows rarely exceeded 85 pounds, with arrow shafts typically no thicker than 9mm or 10mm (Junkmanns 2013). Given these considerations, the thickness of the point may at best exclude the use of a bow, provided that the hafting method is known, but it does not permit identification of the bow or any other weapon system. We therefore propose that there are no reliable grounds to link a specific stone point size (or size range) with a particular mode of propulsion.

Even if TCSA/TCSP measurements and morphometric analyses are attractive and straightforward to perform, our results indicate that the two principles on which the TCSA/TCSP approach is founded are not as robust as previously assumed. Within this framework, shaft widths are generally considered to be relatively uniform along their entire length, an assumption that does not necessarily hold in practice. Tapering of the distal end or using foreshafts can allow small points to be mounted effectively on relatively large shafts. Moreover, as there are no physical principles that establish a direct link between point size and shaft size, morphometric analyses like those used in the TCSA approach rely on ethnographic analogies that have limitations and risks of bias. The gradual elaboration of the ethnographic reference framework has resulted in an important overlap between the morphometric parameters of projectile points for the different propulsion modes. Moreover, a recent survey of ethnographic wooden-tipped spears also highlighted that an important overlap in form exists between throwing and thrusting spears, thereby demonstrating that the morphometric parameters of the shafts are not reliable predictors of propulsion mode (i.e., thrusting or hand-thrown wooden-tipped spears) (Milks et al. 2024). In this study, we demonstrated that the TCSA value and size of a point cannot be directly correlated with a shaft size and propulsion mode and that a diversity of point sizes can be used effectively with each propulsion mode (see Figures S1– S3). Models relying solely on point size and TCSA/TCSP values are therefore unlikely to generate reliable hypotheses to understand prehistoric weapon systems.

Serious questions can thus be raised with regard to the reliability of using point size and TCSA values as arguments to argue for the use of long-range weaponry as is frequently done in broader models on the evolution of Paleolithic weaponry (Backwell et al. 2018; Bradfield et al. 2020; Lombard 2020a, 2021; Lombard and Churchill 2022; Lombard and Phillipson 2010; Metz et al. 2023; Sahle and Lombard 2024b; Sano 2016; Sano et al. 2019; Shea 2006; Shea and Sisk 2010; Sisk and Shea 2011; Yaroshevich et al. 2021). We argue that both the early appearance of long-range weaponry as well as its spread with modern humans are not yet sufficiently supported by reliable evidence to warrant a consensus on this topic. To move forward, we take a differing position in comparison to Lombard et al. (2022) who advocate that TCSA would be an effective tool for constructing large-scale hypotheses and models on the evolution of weaponry and hunting strategies. While we acknowledge that morphometric approaches can be useful in certain contexts, we share the concerns expressed by Milks et al. (2024) that basing hypotheses solely on morphometric analogies may hinder the development of new and innovative hypotheses about Paleolithic weaponry.

Alternative approaches that may provide more reliable data exist and can be explored. Use-wear analyses are known to permit identification of whether stone points were used as projectiles. We have also demonstrated that detailed functional analyses of archaeological points combined with robust experiments can provide information about the weapon delivery system (see Coppe et al. 2023). The latter approach relies on the fact that when stone armatures break upon impact, their fracturing process reflects the mechanical stress generated by the weapon system, which can be identified on the basis of a detailed analysis of the fractures that are visible on a stone point. Each weapon system proves to result in different combinations of mechanical stress (Coppe et al. 2022). A detailed analysis of these fractures combined with an elaborate experimental reference framework and a dedicated sequential experimental program allows identification of the weapon system that was used. In our opinion, the development of models on the evolution of Paleolithic weaponry and the appearance of long-distance weapons would benefit from incorporating functional data more systematically. It is true that functional studies still remain too infrequent and that more functional data need to be generated, but it is doable with a shared effort of the research community. Obtaining the required data requires significant investment but through a collaborative endeavor to more systematically analyze the fracture signals of each archaeological assemblage, a major step can be taken to improve our understanding of projectiles and to develop more solid models on the evolution of prehistoric weaponry.

CONCLUSION

Current models on the evolution of projectile technology and the appearance of long-distance weapons rely mainly on the morphometric characteristics of the stone points, more specifically their TCSA/TCSP values. Despite the popularity of the TCSA/TCSP approach in projectile studies, the reliability of using these morphometric values as proxies for identifying projectile points or specific weapon systems has hardly been explored. The few experimental studies that have been performed have yielded divergent results and the validity of the TCSA approach for meaningful inferences on projectiles has therefore remained under debate. Thanks to a large-scale experimental program incorporating different point morphologies, hafting systems, and propulsion modes, we were able to demonstrate that the two key principles underlying the TCSA/TCSP approach are flawed. We first demonstrated that TCSA/TCSP values are not relevant proxies for a stone point's penetration capacity because these morphometric characteristics are of little significance compared to other variables. We showed that the propulsion mode combined with the morphology of the stone point (i.e., the sharpness of its apex and edges) are more dominant variables for the penetration capacity of a projectile, rendering any influence from the TCSA/TCSP values of the stone points invisible. Secondly, we demonstrated that point size is not strictly linked to a particular propulsion mode and, more precisely, that small points do not imply the use of arrows. Indeed, we showed that a broad range of stone point sizes and morphologies could achieve lethal penetrations in combination with different weapon systems. There are also no physical principles that would establish a direct link between point size and shaft size (and thus propulsion mode) and we conclude that these ideas seem to stem from preconceptions. Our results therefore challenge the relevance of using a TCSA/TCSP approach to study stone points, to assess whether a stone point could have been used as a projectile, or to identify what weapon system was used.

The TCSA/TCSP approach is currently rooted mostly in ethnography and its reference framework has been criticized for its biased and partial nature. While recent studies have significantly elaborated the ethnographic data used in this reference framework, they have not substantially altered this situation and they have actually introduced a new bias given that the additions mainly concerned metal points. Raw material is a crucial factor and the metric characteristics of metal points cannot be simply transferred to stone points. Caution is therefore warranted when such ethnographic analogies are used for archaeological interpretation.

Given the fundamental methodological issues in the TCSA approach and the problems inherent to the reference framework used, we conclude that the model that advocates an early appearance of long-distance weaponry is currently not yet supported. More precisely, both the early appearance of the bow in South Africa and its early arrival in Europe are currently not supported by reliable evidence.

Ethnographic analogies based on point metrics, while interesting, do not appear sufficiently sound to construct models on the evolution of projectile technology, including the emergence and dispersal of long-range weaponry. To guarantee future advances in the study of projectile technology, we advocate a methodological shift toward a more functional approach to the archaeological material in which attention is devoted to macrofractures and microwear, according to the principles of use-wear studies, and which are combined with sequential experimental programs. While such an approach is very time-intensive, we believe that efforts would be rewarded by more robust data and innovative insights that can serve as a basis for developing better models on the evolution of Paleolithic weaponry and its role in human evolution. Such an approach would also permit further reflection on whether long-distance weaponry was indeed the game changer that helped the dispersal of modern humans.

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AUTHOR CONTRIBUTIONS

Conceptualization: J.C., V.R.; Methodology: J.C., V.R.; Formal Analysis: J.C.; Investigation: J.C.; Writing – Original Draft: J.C., V.R.; Writing – Review and Editing: J.C., V.R.; Supervision: V.R.; Project Administration: V.R.; Funding Acquisition: V.R.

SUPPLEMENTARY DATASET

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Supplement 1 to Does Point Size Matter? How Morphometric Arguments Impact Evolutionary Models of Paleolithic Weaponry

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SUPPLEMENT 1

This supplement contains: additional text and Figures S1–S3.

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Details of the large-scale experimental program

Three stone point morphologies (triangular, bifacial, and backed points) in two size categories (small and large) were used during the experiment that is included in this study (TRAIL / Experiment 46). These stone points were hafted on wooden shafts and secured with three different methods: with glue, with sinew bindings, or with a combination of both (i.e., glue and sinew for reinforcement, with additional glue applied to protect the bindings). Subsequently, the points were mounted on either an arrow, dart, or spear shaft.

All examples illustrated below are pieces used during Experiment 46, which achieved a penetration depth equal or above the threshold of 10cm that is considered to be lethal. A schematic representation of the cross-section of the point is integrated below the pictures, as well as some additional details such as the TCSA and TCSP values and the maximum penetration depths as recorded during the experiment. As shown by the penetration depths marked below, small stone points can effectively function on large shafts, and conversely, large points can perform well on small shafts.

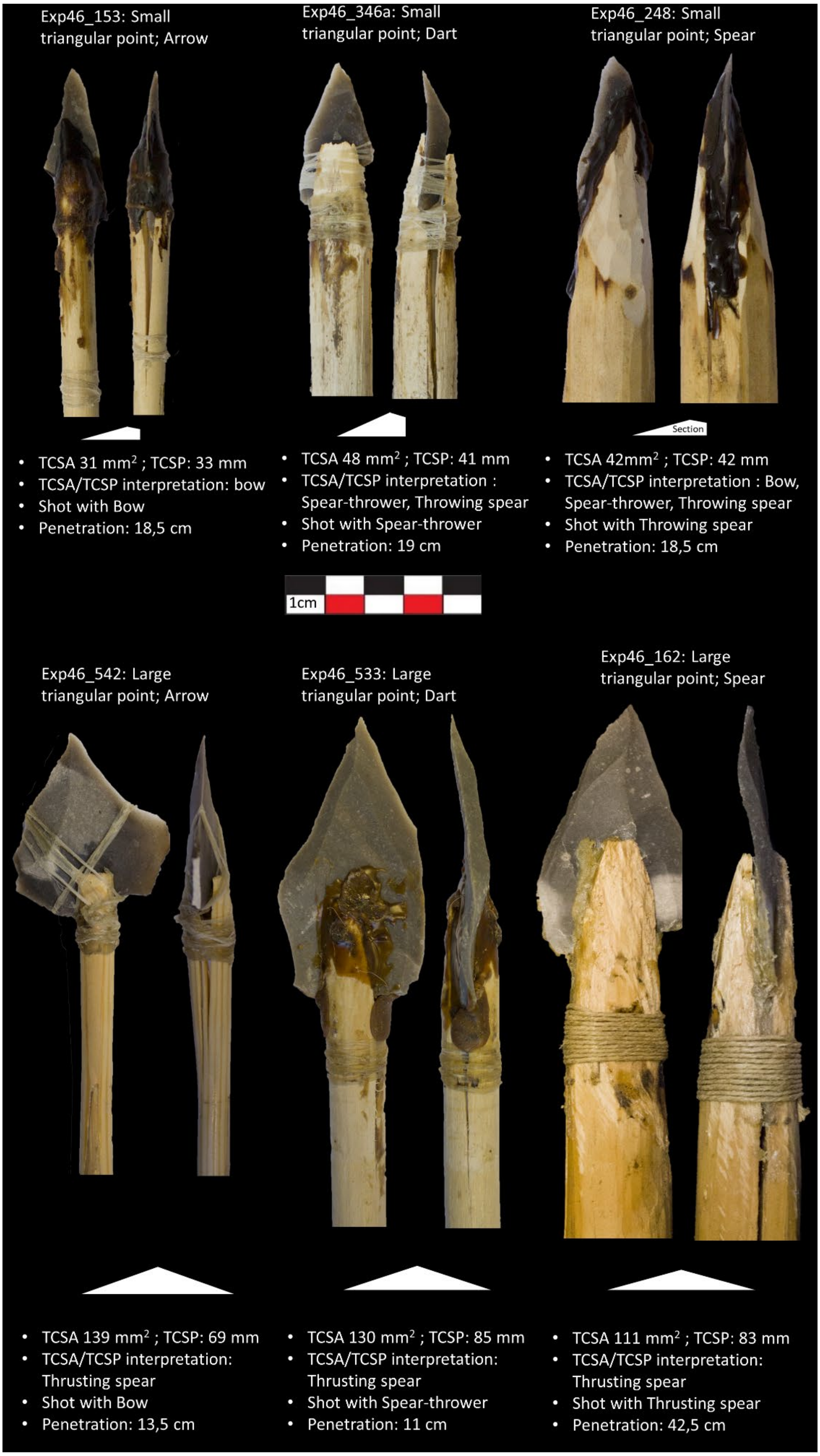

Figure S1. Small and large triangular points used during Experiment 46. The range of measure used for TCSA/TCSP interpretation comes from Lombard (2021: Table 3).

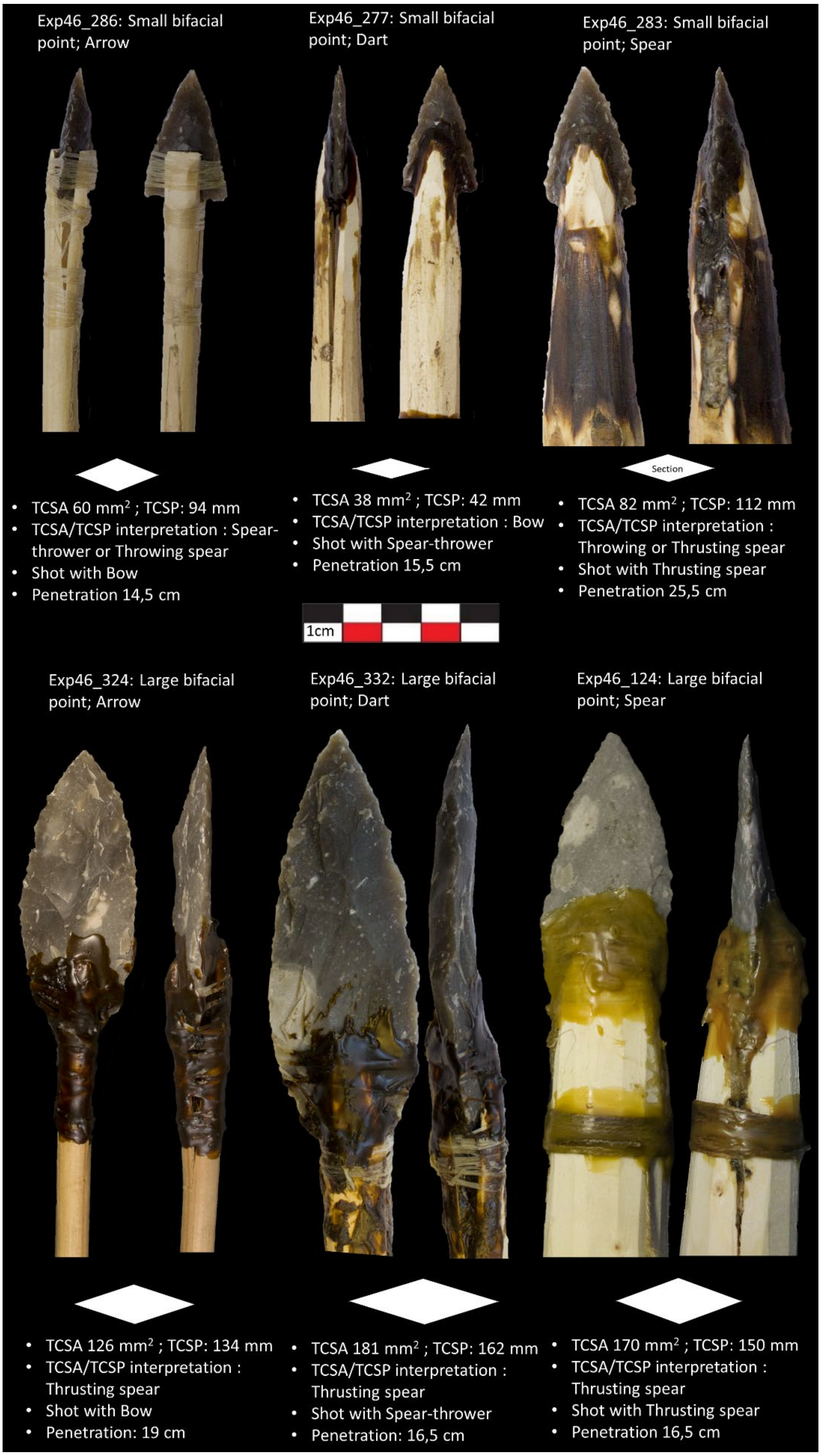

Figure S2. Small and large bifacial points used during Experiment 46. The range of measure used for TCSA/TCSP interpretation comes from Lombard (2021: Table 3).

Figure S3. Small and large backed points used during Experiment 46. The range of measure used for TCSA/TCSP interpretation comes from Lombard (2021: Table 3).