**Does point size matter? How morphometric arguments impact evolutionary models of Palaeolithic weaponry**

Morphometrics & Paleolithic Weapon Evolution

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ABSTRACT

The invention of long-range weaponry has been a pivotal technological change with significant implications for Palaeolithic subsistence strategies and is assumed to have been a crucial factor 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 remains testifying to the use of long-range weaponry are far more recent and the early-appearance model is therefore inferred primarily from 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 hypothesise the use of a particular weapon system. Despite the popularity of TCSA/TCSP in projectile studies, the reliability of using morphometric values to infer a particular weapon system remains insufficiently explored through experimental approaches. To further assess the validity of these proxies, we use the results of a comprehensive multiparameter shooting experiment, the design of which permits to test 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, which proves more influenced by other morphological parameters and by 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 an exclusive relation between small points and the use of arrows. These findings raise important concerns regarding the reliability of the arguments that are currently used to support an early appearance of long-distance weaponry. We encourage an approach that draws more from use-wear studies and sequential experimental programs, to permit the development of more fine-grained models for the emergence of long-range weapon systems.

1. INTRODUCTION

Long-range weaponry is often presented as one of the most significant technological inventions that impacted Palaeolithic subsistence strategies and that may have been critical to the successful spread of anatomically modern humans out of Africa (Marean, 2005; Shea and Sisk, 2010). When and where this invention took place, how it developed over time, how it spread and how it affected the lives of Palaeolithic hunter-gatherer populations are crucial questions in prehistoric research. However, gaining insight into Palaeolithic weaponry and its evolution is a challenge given that most components are made from organic materials, which decay over time, leaving only the durable lithic or organic components as the primary source of information for their reconstruction. A lot of attention has therefore been devoted to the characteristics of the stone points as well as possible traces of impact to evaluate whether these could have functioned as projectile points (Witthoft, 1968; Frison, 1974, 1989; Barton and Bergman, 1982; Bergman and Newcomer, 1983; Fischer et al., 1984; Shea, 1988; Dockall, 1997; Plisson and Beyries, 1998). Over the last 20 years or so, attention has gradually shifted to inferences on the weapon system and it received an increasingly prominent role in broader discussions on the origins of modern human behaviours (McBrearty and Brooks, 2000). A literature review gives the impression that a consensus would have emerged around an early appearance of long-range weaponry, more specifically in Sub-Saharan Africa during the Middle Stone Age, more precisely during MIS 4 (McBrearty and Brooks, 2000; Brooks et al., 2006; Sisk and Shea, 2011; Bradfield et al., 2020; Lombard, 2024). This early-appearance model relies on morphometric data of the stone points and the assumption that the size of the stone points is closely related to the size of the shafts that carried them and therefore permits to infer the propulsion mode. Indeed, authors have argued that some points identified as projectiles are too small to function as anything other than arrow tips (Brooks et al., 2006; Lombard, 2011; Metz et al., 2023), or that "thick points have to be mounted in thick shafts" (Shea, 2009, p. 194). This direct link between the size of the point and the size of the shaft (and therefore weapon system) was formalised 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, introduced by Hughes (1998) and popularised by Shea (2006), are now well-spread in the literature and serve to support most hypotheses on the early appearance of long-range weaponry.

Given the increasing use of TCSA/TCSP values over the past decade, a careful and comprehensive evaluation of their reliability would be beneficial to the research community. After all, the strength of the model proposing the early appearance of long-range weaponry depends directly on the reliability of the underlying data. The hypothesised link between stone point, shaft size and propulsion mode has been explored in relatively few studies with conflicting conclusions (Clarkson, 2016; Sitton et al., 2020; Grady and Churchill, 2023; Pettigrew et al., 2023) . In this article, we examine the reliability of using stone point size to infer shaft size and the weapon system based on 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 Palaeolithic 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.

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

Research on Palaeolithic weaponry and its evolution cannot be disconnected from broader reflections on the evolution of human behaviours and the emergence of complex cognition. Indeed, several technological innovations have been considered as important archaeological indicators 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 et al., 2009; Wadley, 2010; Bradfield et al., 2015), 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), but also projectile technology (Shea, 2006, 2009; Shea and Sisk, 2010; Sisk and Shea, 2011; Wynn and Coolidge, 2011; Lombard and Haidle, 2012; Coolidge and Wynn, 2016, 2016; Coolidge et al., 2016; 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 been observed amongst 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 behaviours, distinctions in subsistence strategies between modern humans and Neanderthals have been proposed (Marean, 2005) as well as contested (Rendu, 2022). Indeed, growing evidence indicates a diversity of practices among Neanderthals, including selective hunting (Gaudzinski, 1996, 2006), exploitation of a wide range of species (both small and large) depending on the context (Blasco et al., 2022; Gaudzinski-Windheuser et al., 2023b) (Gaudzinski-Windheuser et al., 2023a). These discoveries progressively blur presumed differences in hunting behaviours between Neanderthals and modern humans (Villa and Roebroeks, 2014), but also place more emphasis on potentially remaining distinctive traits (Scerri and Will, 2023). Long-range weaponry is one of those remaining traits that is still considered to be strictly limited to modern humans and the appearance of this innovative technology has been considered 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 optimise 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 labour division and social disparities (Grund, 2017).

Current insights in how weapon technology evolved and varied over time and space rely on data of varying 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 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). 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) with evidence for the use of bow-and-arrow having been proposed for the Federmesser (Tomasso et al., 2021). All other published data regarding weapon technology relies exclusively on the analysis of point morphology and point size and it is still uncertain that such traits would allow reliable inferences on projectiles or weapon systems. Such results should thus be considered as hypotheses that may be interesting but require further testing and validation. 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, 2010). Impact fractures are said to support projectile use, but the inferred propulsion mode relies exclusively on point size and the argument that the segments would show broad morphological similarities with known arrowheads such as Late 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 et al., 1974; Clark, 1977; McBrearty and Brooks, 2000). Given that this would represent the oldest evidence for the use of bow-and-arrow, it has been hypothesised that this technology would have originated in the Middle Stone Age of South Africa (McBrearty and Brooks, 2000; Brooks et al., 2006; Shea, 2006; Lombard, 2010; Sisk and Shea, 2011). 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; Lombard, 2010, 2011; Sisk and Shea, 2011; Brown et al., 2012; Lombard and Wadley, 2016; Bradfield et al., 2020) and elsewhere (Langley et al., 2020; Metz et al., 2023) .

As a variant on point size and general 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 intensively debated (Clarkson, 2016; Sitton et al., 2020; Grady and Churchill, 2023; 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 some cases in which projectile use is inferred on the basis of fractures assumed to be 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 is highly variable. In some studies, TCSA values are used to infer the suitability of certain artefacts to have been used as weapon armatures (Brooks et al., 2006; Sahle et al., 2013; Sahle and Brooks, 2019). 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 hypothesises on the propulsion mode, with projectile use being argued for on the basis of impact fractures (Sano, 2016; Sano et al., 2019; Yaroshevich et al., 2021; Metz et al., 2023). In addition to these specific archaeological case studies (Sano, 2016; Sano et al., 2019; Yaroshevich et al., 2021; Metz et al., 2023), TCSA values have also been used for modelling the emergence of long-range weapons on broad geographical and temporal scales (Hughes, 1998; Shea, 2006; Shea and Sisk, 2010; Sisk and Shea, 2011; Lombard, 2020a, 2021, 2021; Lombard and Shea, 2021; Lombard and Churchill, 2022; Park et al., 2023; Sahle and Lombard, 2024a).

Current models based on point size and TCSA/TCSP values hypothesise 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, 2010, 2011, 2020b), 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 (Shott, 1993; Bradbury, 1998) 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 (Christenson, 1986; Blitz, 1988; 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 (Odell, 1988; Amick, 1994). 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 (Corliss, 1972; Thomas, 1978; Amick, 1994) , but TCSA/TCSP values are no doubt the most popular ones.

Susan Hughes (1998) initially introduced the concepts of tip cross-sectional areaandtip 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 .

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

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 characterised 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 to evaluate the capacity of a point to penetrate the target (Hughes, 1998). Several experiments were conducted to explore this relation and all results converge towards TCSP being a more accurate predictor of point penetration than TCSA (Sisk and Shea, 2009; Sitton et al., 2020; Grady and Churchill, 2023).

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 to hypothesise which weapon type would be best suited for the archaeological points (Hughes, 1998; Shea, 2006; Sisk and Shea, 2011; Lombard et al., 2022). However, the reliability of the correlation between TCSA/TCSP values and propulsion modes has been criticised 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, p. 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, at the exception of the ones considered astoo 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 setup did not test their functionality with other propulsion modes. The reliability of the reference for thrusting spear 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 Palaeolithic and Middle Stone Age to the early Upper Palaeolithic (Brooks et al., 2006; Shea, 2006; Villa and Lenoir, 2006, 2009; Shea and Sisk, 2010; Sisk and Shea, 2011; Costa, 2012; Wilkins et al., 2012; Sano, 2016; Lee and Sano, 2018; Serwatka, 2018; Sahle and Brooks, 2019; Sano et al., 2019). Several researchers have since criticised 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 (Thomas, 1978; Shott, 1997). 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 Palaeoindian 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 steel-tipped spears, as well as steel- and bone-tipped poisoned arrows (Lombard, 2020b; Lombard et al., 2022; Sahle et al., 2023; Sahle and Lombard, 2024a). 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. Steel, 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 et al., 2023; Sahle and Brooks, 2019), and heavy throwing and thrusting spears (Sahle et al., 2023). With the integration of more steel-tipped projectiles (Sahle et al., 2023; Sahle and Lombard, 2024b), 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 assessed . It can therefore be questioned whether the current reference framework has any relevance for inferences about Palaeolithic 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, In press). 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 (see 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 (Figure 1, 2; Supplementary file 1).

Une image contenant capture d’écran, diagramme

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Figure 1: boxplot of the distribution of TCSA values of the experimental points grouped by morphological categoryUne image contenant capture d’écran, diagramme

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

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 and Rots, 2017; Coppe, 2020). 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.

The four propulsion modes traditionally considered for the Palaeolithic 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). Standardised 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 1 to 2 mm (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.

|  |  |  |
| --- | --- | --- |
| **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) |

Table 1: Morphological categories of the stone points used in the experiment (Exp46) and the archaeological example used as inspiration for their manufacture.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **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 15 cm from the tip (mm) | 8,5 | 8,5 | 8,5 |
| Dart diameter at 15 cm from the tip (mm) | 13,4 | 14,5 | 15,5 |
| Throwing spear diameter at 15 cm from the tip (mm) | 23,4 | 26,2 | 34,2 |
| Thrusting spear diameter at 15 cm from the tip (mm) | 27 | 28,5 | 30,2 |

Table 2: Physical parameters of the shafts used in the experiment (Exp46).

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 5 cm through skin, fat, and muscle may already be lethal. For the largest animals (e.g., proboscideans), 12 cm is said to be a minimum (cf. Kilby et al., 2022). Frison (1974) reports a lethal penetration depth of 15 cm in his experiments with a Bos taurus (to perforate the heart). Friis-Hansen (1990) reports that 15 cm of depth is required for the rib cage of a roe deer to make it fall after 10 seconds of run. Other studies seem to overestimate the necessary penetration depth and propose that 20 cm is necessary for medium game (Shea et al., 2002; Tomka, 2013; Salem and Churchill, 2016), 25 cm for large game (Tomka, 2013; Sitton et al., 2020) and even 58 cm 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 10 cm as a reliable threshold because this permits the perforation of vital organs for most medium to large game (e.g., cervid, horse, wild boar, bovid) and can thus be considered as fatal (Mertz, 2010; see also fig 116 in Pavaux, 1982).

# 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 these shots permitted to exploit data on penetration depths (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%), the rebound of projectiles on the skin (41%, mostly bifacial points), or the fracturing of the point upon contact with the target (16%, mostly backed points). Penetration depths ranged from 0 to 66 cm and 321 shots (63%) can be considered as lethal since their penetration exceeded 10 cm in depth (Table 3).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **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 |

Table 3: Penetration depths recorded for the 507 shots conducted during the experiment (Exp46), organised according to the three main parameters that were tested— propulsion mode, hafting system, and point morphology (S= sinew, G= glue, GSG= glue-sinew-glue).

## WHAT VARIABLES INFLUENCE THE SUCCESS RATE OF PROJECTILES TO PENETRATE 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 or failure 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 (χ²= 13.3, df 5, p=0.021) with small and large bifacial points having most difficulty to penetrate the 2 mm pony skin compared to other point morphologies (small bifacial points: 74% of success; large bifacial points: 77% of success). Triangular points, both small and large, prove most successful at penetrating the skin (large triangular points: 89% of success; small triangular points: 91% of success) (Figure 3a). Also the hafting mode proved to significantly influence the success with which projectiles penetrated the skin (χ²= 7.51, df 2, p=0.023). Points that were simply glued to the shaft proved most successful (89% of success) while points secured with sinew bindings only were least successful (78% of success) (Figure 3b). The mode of propulsion did not appear to significantly affect the success rate with which projectiles penetrated the skin (χ²= 0.735, df 3, p=0.865) (Figure 3c).

All TCSA/TCSP values of the stone points were recorded (Figure 1, 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 to penetrate the skin and those that failed (Figure 4, 5). This was confirmed by a Mann-Whitney U test (TCSA: WMW = 16184, p = 0.376; TCSP: WMW = 15506, p = 0.148).

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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.

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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.

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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.

## WHICH VARIABLES INFLUENCE THE SUCCESS RATE OF PROJECTILES TO REACH LETHAL PENETRATION DEPTHS (10 CM OR MORE)?

Each point morphology successfully reached penetration depths of 10 cm 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 spear and the large bifacial point combined with the spear-thrower, compared to other combinations (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 10 cm or more. Only the propulsion mode proved to be significantly influential (χ² = 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 (χ² = 0.261, df = 2, p = 0.878) and point morphology (χ² = 8.54, df = 5, p = 0.129) do not significantly influence the frequency of reaching penetrations of 10 cm 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 morphologies) 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 (Figure 6). Indeed, no significant influence of TCSA/TCSP values on the success rate of reaching penetration depths of 10 cm 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).

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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.

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Figure 7: Proportion (%) of the shots that reached penetration depths above or below the threshold of 10 cm 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.

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Fig 8: Correlation chart comparing penetration depth with TCSA/TCSP values of the points, organised by mode of propulsion.

## 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 to accommodate most point sizes on any shaft (see below for more details) (Figure 13, Figure S1, Figure S2, Figure 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 hypothesise the use of the bow on 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, thirty-six points nevertheless meet this criterion, (Table 4 and 5).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **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 4: TCSA/TCSP characteristics of the 36 pieces selected from the experimental reference set that respect the maximal cutoff of 10 mm in width

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

Table 5: Number of points and shots per mode of propulsion

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

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

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 (Figure 9, 10). We note that the range of TCSA values per weapon delivery system (Figure 9) crosscuts ranges considered by some researchers as being ideal for poisoned (TCSA between 4–18 mm2) and unpoisoned arrow tips (TCSA between 17–47 mm2) (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). Ranges of penetration depths were comparable between arrows and darts, 0-22.5 cm and 0-21 cm, respectively. The range of penetration depths for thrusting 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 10 cm. 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, Figure 11). Aside from the throwing spear reaching lower penetration depths overall, all propulsion modes prove to inflict lethal wounds when combined with small stone points, though this is less frequent for throwing spears (Figure 11).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **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 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.

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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 10 cm used in this study for lethal wounds in the case of medium-sized to large-sized game.

We also compared the distribution of penetration depths for shots with points below or above 10 mm 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 (Table.7, Figure 12).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **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 |

Table 7: Summary of the results obtained for the penetration depths (in cm) grouped by propulsion mode. Results are compared between the 59 shots performed with the 36 smallest points in the sample (10 mm or less in width) and the 448 shots performed with the 241 larger points (above 10 mm in width).

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These results indicate that both small (10 mm 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 10 mm 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 more 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 (Wilkins et al., 2012; Sahle et al., 2013) and the appearance of long-distance weaponry (Backwell et al., 2008, 2018; Lombard, 2010, 2011, 2020b, 2021; Sisk and Shea, 2011; Lombard and Wadley, 2016; Sano, 2016; Sahle and Brooks, 2019; Sano et al., 2019; Langley et al., 2020; Lombard and Shea, 2021; Yaroshevich et al., 2021; Lombard and Churchill, 2022, 2022; Metz et al., 2023; Sahle and Lombard, 2024b). The latter is fundamental for broader debates on the evolution of Palaeolithic weaponry, but also for human evolution. After all, the use of long-distance weaponry is considered to be exclusive to modern humans and a game changer for a successful dispersal out of Africa (Shea, 2009; Sisk and Shea, 2011).

When addressing projectile point identification, such studies rely on the principle that a point’s metrics permit to evaluate its capacity to penetrate a target even though this does not imply that the stone point would actually have been used as a projectile. Nevertheless, the pointed morphology combined with TCSA/TCSP values and sometimes other lines of evidence are regularly considered sufficient grounds to argue for projectile use. 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 hypothesised as being the best suitable shaft width and the most likely propulsion mode is subsequently deduced. In this study, we aimed to test the reliability of both principles because they underlie the TCSA approach that is now commonly used in projectile studies. To do so, we used a large experimental projectile reference collection available at TraceoLab, University of Liège (Experiment 46 of TRAIL). The goal was to evaluated whether both principles are valid and can be used as reliable grounds to support the validity of the TCSA approach for inferences on projectile use and propulsion modes.

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). Highly controlled experimental set-ups were used and a maximum number of parameters were kept constant. Also the point morphology was controlled, 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 grinded 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), 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 permitted to show 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 secondary once the skin is pierced to widen the hole (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 constitutes 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 significantly influences 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 2900 J, 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 (average value for bow: 28 J, for spear-thrower: 44 J, for throwing spear: 72 J; 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; Reyssat et al., 2012; Mora and Pomeau, 2020; Mora, 2021; Goda et al., 2023). 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 localised. The faster the slicing motion, the more localised 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; Reyssat et al., 2012; Mora and Pomeau, 2020; Mora, 2021; Goda et al., 2023). 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: 45 m/s) compared to other (slower) propulsion modes (average dart speed: 25 m/s; average throwing spear speed: 14 m/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 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: 14.5 mm; mean thrusting spear width: 28.5 mm) (Figure S3). These findings therefore disprove the hypothesis that points of 10 mm width or less are only functional when used with arrows, as argued by Metz et al. (2023). Given that point size combined with TCSA values are the only arguments put forward to support the use of the bow, our results invalidate the interpretation of Metz et al. (2023). A similar case can be made for the early appearance of the bow in South Africa, as proposed by Lombard (Lombard, 2011). Such interpretations 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. 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 (Feugère, 1993; Bishop, 2017)

. This weapon featured shafts weighing between 200 g and 1700 g, with a steel foreshaft measuring between 27 cm and 120 cm in length and with a notably reduced diameter, which as such tapers the distal end of the javelin. These foreshafts were tipped with a pyramidal point measuring between 7 and 33 mm in width (Bishop, 2017). Stone points of a width of 10 mm 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 optimise the distal tapering of the throwing spears in order to maximise their penetration capacity, because our primary goal was to achieve a penetration of minimum 5 cm and reach the ribs of the target. As a result, we attribute the lower success rate in reaching penetrations above the lethal threshold (i.e. 10 cm 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 enhanced their penetration capacity even more (see 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.

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Figure 13: Three examples of throwing spears with stone points of less than 10 mm 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.

Small stone points can thus function perfectly on large shafts, but also the opposite scenario 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) (Figure S1) and large bifacial points (Still Bay points) onto arrows (on split shafts) (Figure S2), as well as small backed points (microgravettes) onto throwing and thrusting spears (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 shafts. Points that are more than 4 mm thicker than the shaft’s diameter could not be securely hafted with our hafting system, which set the maximal thickness of the arrowpoints on 12.5 mm 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 8.5 mm in diameter. It seems unlikely that Palaeolithic arrowpoints hafted onto split shafts could have exceeded 14 mm 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 Palaeolithic bows, and the associated arrow shafts had diameters between 11 and 13 mm (Alexzandra, 2011). Neolithic bows rarely exceeded 85 pounds, with arrow shafts typically no thicker than 9 or 10 mm (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 to identify 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. Since there are no physical principles that establish a direct link between point size and shaft size, morphometric analyses like the TCSA approach rely on ethnographic analogies which have significant limitations and risks of bias. The gradual elaboration of the ethnographic reference framework has only led to more 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 (Figure S1, S2, S3). Models relying solely on point size and TCSA/TCSP values are therefore unlikely to generate reliable hypotheses to grasp 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 frequently done in broader models on the evolution of Palaeolithic weaponry (Shea, 2006; Lombard, 2010, 2020a, 2021; Shea and Sisk, 2010; Sisk and Shea, 2011; Sano, 2016; Backwell et al., 2018; Sano et al., 2019; Bradfield et al., 2020; Yaroshevich et al., 2021; Lombard and Churchill, 2022; Metz et al., 2023; Sahle and Lombard, 2024b). 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 than 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 Palaeolithic 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 (e.g., Rots and Plisson 2014). 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 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 to identify the weapon system that was used. In our opinion, the development of models on the evolution of Palaeolithic 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 when collaborative efforts are invested in more systematically analysing the fracture signals of each archaeological assemblage, a major step can be taken in improving our understanding of projectiles and in developing 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, keeping the validity of the TCSA approach for meaningful inferences on projectiles under debate. Thanks to a large-scale experimental program incorporating different point morphologies, hafting systems, and propulsion modes, we could 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 and 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 in ethnography mostly and its reference framework has been criticised for its biased and partial nature. While recent studies have significantly elaborated the ethnographic data used in this reference, it has not substantially altered the situation and it has 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 enough 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 Palaeolithic weaponry and its role in human evolution. Such an approach would also permit to further reflect on whether long-distance weaponry was indeed the game changer that helped the dispersal of modern humans.

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## AUTHORS 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

<https://zenodo.org/records/14945064>

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