Stone Tip Cross-Sectional Geometry Contributes to Thrusting Spear Performance

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submitted: 13 February 2025; revised 11 May 2025; accepted: 16 May 2025

Handling Editor in Chief: Karen Reubens

ABSTRACT

Humans around the world likely used thrusting spears during much of the Paleolithic period. A key development in spear evolution was the addition of a sharp stone tip. Here, we examined via controlled experiment whether stone tip cross-sectional geometry (i.e., tip cross-sectional area, TCSA; tip cross-sectional perimeter, TCSP) contributes to thrust spear function in terms of two performance variables: penetration depth and entry wound width. We produced 14 spears, each possessing a different stone tip form at its end. A trained army veteran thrust each spear several times into ballistics gel, for a total sample size of 387 thrusts. Statistical analysis revealed a strong inverse relationship between stone tip cross-sectional geometry and penetration depth and a positive relationship between stone tip cross-sectional geometry and entry wound width. Overall, these results are consistent with the hypothesis that thrust spear functional performance may have been a factor Paleolithic people considered in producing and selecting stone point forms. Additionally, our results suggest that there may have been a tradeoff among the performance attributes of penetration depth and entry wound width, each of which may have been preferred in specific contexts.

***P**aleo**A**nthropology* **2026:1: 26-45** **https://doi.org/10.48738/2026.iss1.3863** **ISSN 1545-0031**
Paleoanthropology Society & European Society for the study of Human Evolution.
OPEN ACCESS
Early View available online 28 May 2025

INTRODUCTION

Two activities crucial to the survival and evolution of Pleistocene hominins—indeed, any organism—would have been successful procurement of resources and effective self-defense against predators. Any behavior or technology that increased the chances of acquiring assets or deterring death likely would have been transmitted widely and ultimately fixed in the hominin cultural repertoire. It is in this light that we view the emergence of the spear, plausibly the first hunting and self-defense implement widely employed by hominins (Milks 2020; Milks et al. 2016: 192; but also consider Cabanès et al. 2024; Roach and Richmond 2015; Wilson et al. 2016). Capable of high and sustained kinetic energy (Coppe et al. 2019; see also Bebber et al. 2023, 2024; Gaudzinski-Windheuser et al. 2018; Milks et al. 2016; Porta 2019) with "few points at which failure can occur" relative to more complex weapon systems (Hitchcock and Bleed 1997: 359), the spear would have facilitated hominin acquisition of medium to large sized animals (Churchill 1993) and provided a means of deterrence—via pain or death—against predation (Baldino et al. 2024; Milks et al. 2016; Russo et al. 2023). Moreover, as Pickering and Domínguez-Rodrigo (2010: 111) suggest, even the simplest extrasomatic hunting technology provides at least some measure of distance between predator and prey, which is important because even "small prey… can inflict counter-attacking injuries upon a predator." Thus, like other technological 'watershed' developments, such as the adoption of cutting implements (Biermann Gürbüz and Lycett 2021; Eren et al. 2025) or the control of fire (Alperson-Afil 2008; Shimelmitz et al. 2014; Shea 2023), spear use would have plausibly provided a selective advantage to Pleistocene hominins. However, these benefits did not come without costs, perhaps the most prominent being the time and energy invested in spear production (Barham 2013; Shea 1997). Different types of wood can exhibit vastly different properties, likely recognizable by hominins (Milks 2021), who would have incurred learning costs and possibly procurement costs for desired wood types not locally available. Paleolithic spear-use would have also come with substantial costs for teaching and learning (Lew-Levy et al. 2022; Milks 2024).

Definitive evidence of spears in the archaeological record dates to the mid-Middle Pleistocene and takes the form of preserved wooden examples at Schöningen (200–320 kya; Biermann Gürbüz and Lycett 2020; Richter and Krebtschek 2015; Thieme 1997; but see Hutson et al. 2025) and Clacton-on-Sea (400 kya; Allington-Jones 2015; Oakley et al. 1977). However, spear use likely emerged earlier. Wilkins et al. (2012, 2014; 2015; Wilkins 2018; Wilkins and Schoville 2016; see also Schoville et al. 2016) provide a clever and elegant inferential case for stone-tipped spears dating to ca. 500 kya. at Kathu Pan, South Africa. Hunting lesions on animal bone at Boxgrove, U.K., may be indicative of spear use at ca. 500 kya (Roberts and Parfit 1999; but see Gaudzinski-Windheuser 2016: 92). Domínguez-Rodrigo et al. (2001: 298) suggest that phytoliths recovered on Acheulean stone tools at Peninj, Tanzania, may indicate the manufacture of "rudimentary spears" (among several possibilities). Bearded capuchins (*Sapajus libidinosus*) manufacture probes with thinned tips out of small sticks, which they use to poke at small prey animals (Biermann Gürbüz and Lycett 2020; Falótico and Ottoni 2014). And given documented spear-use among some chimpanzees (Micheletti et al. 2022; Nakamura and Itoh 2008; Pruetz and Bertolani 2007; Pruetz et al. 2015), Pickering and Domínguez-Rodrigo (2010: 111) suggest that "early hominids may have hunted (at least sometimes) using rudimentary, perishable weaponry" while Iovita and Sano (2016: 294) intriguingly propose that "weapons per se were part of the 'package' of complex tool use since the time of the last common ancestor" (see also Agam and Barkai 2018: 3)[1].

Spear use continues during the late-Middle Pleistocene and into modern periods. Sahle et al. (2013) infer that stone-tipped spear use dates back to ca. 279,000 B.P. from the Gademotta Formation in Ethiopia. The Lehringen wooden spear from Germany dates to 130,000–115,000 B.P. (Movius 1950; Thieme and Veil 1985). Several later Pleistocene finds from Europe, Australia, and South America may also be indicative of spears or spear-use (see references in Milks 2020, 2021; see also Boeda et al. 1999; Gaudzinski-Windheuser et al. 2018; Milo 1998; Yaroshevich et al. 2023). Ancient and historic societies often equipped soldiers with spears (e.g., Horn 2013; Keeley et al. 2007; Leshtakov 2011; Murray et al. 2012) and use of spears in small-scale societies is well-documented (Barham 2013; Dira and Hewlett 2016; Hitchcock and Bleed 1997; Lew-Levy et al. 2021; 2022; Milks 2018, 2020, 2024; Milks et al. 2024; Sahle et al. 2023; see also Agam and Barkai 2018 and Kilby et al. 2022, compare with Eren et al. 2022a).

For the majority of humanity's past, wooden spears may have prevailed (Gaudzinski-Windheuser 2016: 96; see also Iovita and Sano 2016; Milks 2021; Waguespack et al. 2009; Wilkins et al. 2014). However, several researchers have suggested that adding a sharp stone tip—whenever and wherever that occurred—would have provided important functional performance benefits to spears (Barham 2013). Sharp-stone tips may facilitate weapon hide-penetration and promote deeper penetration overall (e.g., Ellis 1997; Frison 2004; Grady and Churchill 2023; Hughes 1998; Pettigrew et al. 2023; Petillion et al. 2011; Waguespack et al. 2009; but see Holmberg 1994; Salem and Churchill 2016; Wilkins et al. 2014). Gaudzinski-Windheuser (2016: 78) asserts that animals struck by weapons without cutting edges take longer to die and thus require more tracking. But a spear tipped with a sharp stone instead results in massive blood loss and kills more quickly. Wilkins et al. (2014) also suggest that, when compared to pointed wooden spears, stone-tipped spears create a significantly larger inner wound cavity that widens distally. But again, these possible benefits likely did not come without costs. Shea (1997: 80) notes that the time and energy needed to acquire materials (e.g., wood + stone + mastic + binding) and assemble a stone-tipped spear would have exceeded that required for pointed wooden spears (see also Barham 2013). Shea (1997: 80) also proposes that stone-tipped spears may have decreased functional versatility, and increased risk of equipment failure, relative to pointed wooden spears (see also Wilkins et al. 2014: 2). In sum, the stone-tipped spear is an “important milestone” in hominin technology, “both in terms of the investment of labor before use and in terms of functional specialization” (Shea 1997: 80).

Many more experiments are necessary to assess the costs and benefits of pointed wooden spears versus stone-tipped spears before any broad conclusions can be drawn (Eren and Meltzer 2024). However, also of interest is whether different stone point forms influence a spear’s functional performance, which is our focus in the present study. Several experimental studies have demonstrated that smaller point tip geometries can contribute to deeper *projectile* penetration (e.g., Chen et al. 2022; Conrad et al. 2023; Grady 2017; Grady and Churchill 2023; Howe 2017; Mika et al. 2020; Mullen et al. 2021; Paige et al. in press; Salem and Churchill 2016; Sisk and Shea 2009; Sitton et al. 2020; 2023). Here, we expand on this topic by investigating *thrusting* spears[2] via two questions: (1) Do smaller stone tip geometries contribute to deeper thrusting spear penetration? (2) How does stone tip geometry influence thrusting spear entry wound size?

While several stone-tipped spear-thrusting experiments utilizing human participants[3] have been published (Coppe et al. 2019; Gaudzinski-Windheuser et al. 2018; Milks et al. 2016; Schmitt et al. 2003; Smith et al. 2020), only a few examine the potential influence that stone tip form has on thrusting spear performance. Huckell (1982) thrust Clovis point-tipped spears into an elephant carcass and reported five different penetration depths of 5.9cm, 7.5cm, 25.5cm, 26.0cm, and 27.4cm. While placing a spear thrust into either the rib cage or abdominal region may have influenced penetration depth variation (Huckell [1982] does not report which penetration depths occurred in which region), the experimental Clovis stone tips he used had different tip cross-sectional geometries. It is thus possible that the stone tip form also contributed to the penetration depth variation in Huckell’s (1982) study. In a wide-ranging study experimentally investigating various Paleolithic weapon systems, Lynch (2023: 255–256) reports on four thrusts of basalt biface-tipped spears into a reindeer carcass. Three thrusts were into the rib cage and achieved penetrations of 0cm, 0cm, and <1.5cm; one thrust into the stomach reached 5.0cm. These results are likely due predominately to thrust placement (Lynch 2023: 256). However, like Huckell’s (1982) experimental replicas, Lynch’s (2023: 253) also possessed different stone tip cross-sectional geometries. Baldino et al. (2024) investigated seven different Clovis stone tip forms on thrusting spears and whether they resulted in different penetration depths and wound entry sizes in ballistics gel. They did, but the relationship between tip cross-sectional geometry and functional performance was not analyzed. Finally, Porta (2019) examined spear thrusts of different Middle Paleolithic stone-tipped spear replicas into roe deer carcasses. She explicitly analyzed the relationship between tip cross-sectional geometry and penetration depth and found little correlation (Porta 2019: 334–335). However, given that she subsequently reports that spear impact into hard versus soft tissues predicted penetration depth (Porta 2019: 336–337), her tip cross-sectional geometry results may have been confounded, especially given her small sample sizes. Moreover, it appears the roe deer may not have been appropriate targets for assessing deep penetration. The roe deer was relatively narrow (e.g., Porta 2019: 214), and spears were, at least occasionally, thrust entirely through it (e.g., Porta 2019: 257). But since there was nothing on the other side of the carcass once the spear had passed through, no further resistance was encountered (see Hunzicker personal communication in Eren et al. 2021). Thus, it is unclear whether Porta’s (2019) experiment was designed to yield accurate penetration data, especially with regard to the potential influence of stone tip cross-sectional geometry.

MATERIALS AND METHODS

Much of the materials and methods for this study have been reported previously in different experiments. We summarize them here, but further details can be found in Sitton et al. (2020; 2023), Baldino et al. (2024), Buchanan et al. (2022), and Mika et al. (2023).

EXPERIMENTAL STONE POINTS AND POINT GEOMETRY METRICS

Fourteen forms of lanceolate stone projectile point (Figure 1**)** were produced via lapidary equipment by Craig Ratzat (Neolithics Flintknapping Supply House, www.neolithics.com) using heat-treated Texas Fredericksburg chert (Sitton et al. 2020). Blind to the goals of the experiment, Ratzat pressure flaked the edges of all points to sharpen them. We chose these 14 point forms as they represent a large amount of real or theoretical variability in the Clovis culture, a late Pleistocene archaeological culture in North America (for details, see Eren et al. 2020).

Many potential variables can be used to calculate point cross-sectional geometry (Sitton et al. 2023). Here, we use two of the most often mentioned and used: tip cross-sectional area (TCSA) and tip cross-sectional perimeter (TCSP). Following Hughes (1998), these variables are defined as

$$TCSA = (½)(w_{tip})(t_{tip})$$

and

$$TCSP = (4)(sqrt((w_{tip}/2)^2 + (t_{tip}/2)^2))$$

where w and t are the width and thickness of the point measured at the widest location on the point. Table 1 provides the TCSA and TCSP of the 14 point forms used in the present experiment, which we calculated from the width and thickness of the stone point exposed just above the lashings (Table 2).

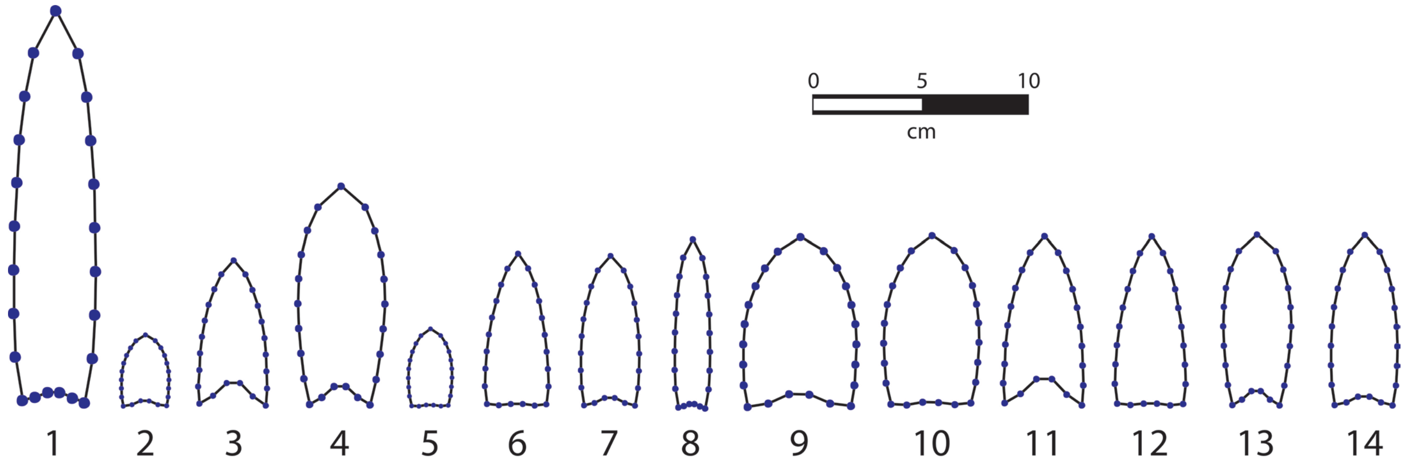

Figure 1. The 14 stone-tip forms used in the experiments. The blue dots are the semi-landmarks used in geometric morphometric analysis.

HAFTING

Although there are exceptions, archaeologists often do not know what type of organic materials Paleolithic people used in the construction of their weaponry, much less the vast diversity of materials that could have been used around the world (and no single experiment could simultaneously test that vast diversity even if it were known) (Conrad et al. 2023; Eren et al. 2022a). Thus, our goal for hafting the 14 point forms was simply to provide a straightforward, safe, secure, and repeatable means by which the points could be used in experimental spear thrusting. We achieved our hafting goals in no small part due to the use of modern "proxy" materials. Relative to materials used in the past—which may be variable, inconsistent, expensive, or completely unknown—the use of modern proxy materials can be valuable in experimental archaeology for increas-

TABLE 1. TCSA AND TCSP OF THE 14 STONE POINT SPEAR TIPS USED IN THE EXPERIMENT.*

Point	TCSA (mm²)	TCSP (mm)
1	157.63	81.75
2	57.80	41.04
3	92.13	56.46
4	159.71	78.66
5	57.45	40.81
6	92.41	57.08
7	86.21	52.43
8	47.19	34.88
9	184.53	99.81
10	192.90	91.75
11	121.52	69.21
12	120.88	75.62
13	104.48	55.21
14	106.91	57.07

*We note that these values are close to, and correlate highly with, those from Sitton et al. (2020), but are not a perfect match. This could be due to slight differences in point form introduced during their manufacture, the fact that the points here were sharpened while those in Sitton et al. (2020) were not, the location of measurements, or inter-observer measurement error.

TABLE 2. MORPHOMETRIC DATA RECORDED FROM THE 14 SPEARS USED IN THE EXPERIMENT.

Spear	Mass (g)	Total Spear Length (cm)	Blade Length Exposed (mm)	Point width at lashing top (mm)	Point thickness at lashing top (mm)	Total Lashing Length (mm)	Maximum Lashing Width (mm)	Maximum Lashing Thickness (mm)	Shaft Diameter (mm)	Shaft width at lashing bottom (mm)	Shaft thickness at lashing bottom (mm)
1	1010.5	195.0	104.28	40.11	7.86	101.97	41.12	32.01	32.66	33.35	31.70
2	759.0	182.1	19.47	19.66	5.88	32.40	20.12	11.66	32.17	18.19	10.50
3	837.0	189.5	49.71	27.42	6.72	41.72	29.68	15.41	31.82	23.03	13.95
4	905.0	189.0	53.25	38.44	8.31	73.90	38.75	31.30	32.61	31.11	30.20
5	724.0	184.7	24.17	19.54	5.88	33.64	20.40	11.89	31.92	18.60	11.63
6	838.5	187.6	44.12	27.75	6.66	49.23	32.58	15.77	32.22	23.20	14.73
7	711.5	186.9	41.51	25.32	6.81	49.07	27.36	15.18	31.78	23.09	14.71
8	762.5	189.7	56.55	16.47	5.73	36.51	18.44	16.04	32.49	17.24	15.34
9	773.5	187.6	53.37	49.34	7.48	54.28	50.95	24.79	31.74	31.96	24.49
10	928.0	189.5	52.27	45.07	8.56	52.77	45.83	21.35	32.24	30.04	21.25
11	927.0	187.0	48.75	33.85	Above Adhesive: 7.18; On Adhesive: 9.13	56.66	37.44	25.42	32.26	28.36	24.46
12	816.5	188.1	48.41	37.25	6.49	54.99	37.34	26.97	32.35	31.17	26.57
13	864.5	189.5	62.83	26.45	7.90	31.98	26.92	17.09	32.44	24.61	15.85
14	916.5	189.7	50.28	27.45	7.79	41.71	28.64	19.33	32.63	26.45	18.50

Figure 2. The 14 finished spears used in the experiments.

ing test control, lowering experiment costs, facilitating trial and test repeatability, augmenting sample size, and even enabling an experiment to be conducted at all (e.g., Dibble and Whittaker 1981; Dogandžić et al. 2020; Eren et al. 2022b; Neill et al. 2022; Schillinger et al. 2014; Schunk et al. 2023; Speer 2018).

One of us (Wilson) hafted the 14 point forms onto Southern Yellow Pine (*Pinus palustris*) shafts, ~1¼-inch in diameter (31–33mm) (see Baldino et al. 2024). After cutting pockets into each shaft into which the points were fitted, we used Ferr-L-Tite thermoplastic adhesive (Wilson et al. 2021) and a synthetic sinew, which is a multi-strand polyester filament product rated at 0.483 N/mm² (Newtons per square millimeter)]-tensile strength (70-pound per square inch), to attach the points. To combine all the components, we used Sterno™ gel canned heat. We added a final coating of water-based polyurethane to protect the bindings so they would not unravel after multiple spear thrusts (Baldino et al. 2024).

Basic morphometric data recorded from the fourteen spears used in the experiment are available in Table 2. Figure 2 shows each of the 14 finished spears.

SPEAR THRUSTING PROCEDURE

We performed our experiment at the Kent State University Experimental Archaeology Laboratory, a controlled indoor setting (Baldino et al. 2024). One of us (Taylor) thrust each of the 14 spears into commercially purchased Clear Ballistics 20% Gel blocks that did not require production, refrigeration, nor calibration by the authors (www.clearballistics.com) (Mullen et al. 2023) (Figure 3; see also images in Baldino et al. 2024). There is a lot of controversy on what type of target simulant should be used for ballistic testing (Jussila 2004), with no end or clear answers in sight (see Mullen et al. 2023). Although Mullen et al.'s (2023) static testing showed that 20% Gel is similar in some respects to biological tissue, we chose this target simulant merely as a uniform substrate that could be used to clearly assess the potential relationship between point form and relative penetration depth.

The gel block was stabilized between a piece of wood and several layers of foam and cardboard such that it did not wobble during spear thrusts. Taylor, blind to the experiment's goals, is an army veteran with experience training with bayonets and hand-to-hand combat (Milks 2019).

Figure 3. Left: Taylor thrusts a spear into ballistic gel while McKinny times how long the thrust should be sustained. Right: a spear before (above) and after (below) being thrust into the ballistics gel block.

He is right-handed and quite strong, and at the time of the experiment (January/February 2023), he possessed a maximum bench press of 355 lbs. and a maximum overhead barbell press of 255 lbs. Except for spear #8, Taylor thrust each of the 14 spears into the gel target 29 times. The stone point (form #8) on spear #8 became dislodged from the shaft on its 11th thrust. In total, the present study reports on 387 spear thrusts. The order of spears was #1 through #14 continually throughout the 387 thrusts. We used three gel blocks over the course of the experiment, with block #1 absorbing thrusts 1–147, block #2 absorbing thrusts 148–283, and block #3 absorbing thrusts 284–387.

To ensure consistent spear thrusts and avoid any fatiguing effects, sets of 14 thrusts—each thrust using a different form—were recorded (Baldino et al. 2024). Additionally, we placed tape marks on the floor where Taylor placed his feet during each thrust. We also placed marks at 55cm (left hand) and 81cm (right hand) distance from each spear's tip where Taylor placed his hands during each thrust. Taylor set the tip of each spear on the surface of the gel before each thrust, and simply pushed forward with each thrust to eliminate variation and inaccuracy that might arise during a backwards-forwards "heave-ho" thrust. Finally, Taylor was told when to begin his forward spear-thrust, timed for one second. At the end an alarm alerted him to stop exerting force. We fully acknowledge that this protocol likely reduced the potential kinetic energy that a thrust spear can impart to a target (Coppe et al. 2019). However, in this paper we are interested in understanding the potential contribution of point form on thrust spear relative penetration depth, and thus we chose to turn down the noise that a fully dynamic thrust may have imparted to the data. Beneficially, our controlled procedure ensured that no spear thrust intersected with any other previous thrust wound channel.

We measured penetration depth by holding the spear shaft at the location at which the shaft was first exposed in the gel target. After removing the spear from the target, we measured the distance from the person's fingers to the spear's tip (Baldino et al. 2024). We measured entry wound size as the length of the incision on the surface of the gel target. Given that the angle of penetration can influence penetration depth (Coppe et al. 2022; Eren et al. 2021), we also

TABLE 3. PENETRATION DEPTH SUMMARY STATISTICS PER SPEAR TYPE.

Spear	Sample size	Mean	Standard deviation	Min	Q1	Median	Q3	Max	Range
1	29	5.71	0.7475	3.6	5.20	5.9	6.20	7.0	3.4
2	29	8.91	1.4222	6.1	7.80	9.1	9.70	11.3	5.2
3	29	7.46	1.2740	4.8	6.50	7.5	8.40	9.8	5.0
4	29	4.45	0.5901	3.3	4.10	4.3	4.60	6.1	2.8
5	29	8.93	1.2599	6.5	8.00	9.1	10.00	11.5	5.0
6	29	8.76	1.6349	5.8	7.90	8.8	10.00	11.5	5.7
7	29	8.46	1.4728	5.5	7.30	8.5	9.60	11.0	5.5
8	10	11.02	1.0184	9.2	10.35	11.2	11.68	12.5	3.3
9	29	3.56	0.4886	2.6	3.30	3.5	3.80	4.5	1.9
10	29	3.66	0.4637	2.7	3.40	3.5	4.10	4.4	1.7
11	29	5.10	0.6729	3.3	4.70	5.0	5.50	6.7	3.4
12	29	5.26	0.6153	4.5	4.80	5.3	5.50	7.1	2.6
13	29	6.90	0.8932	5.2	6.20	7.1	7.50	8.6	3.4
14	29	7.22	0.9839	5.8	6.2	7.2	8	8.7	2.9

recorded the distance between the "wound" and the top of the gel target (Baldino et al. 2024). This measure acted as a proxy for the angle of penetration (hereafter we refer to this as 'angle of penetration').

STATISTICAL ANALYSIS

We carried out our spear thrusting experiment by examining penetration depth and wound width with separate Bayesian regression models implemented in R 4.4.0 (R Core Team) with the *brms* package (Bürkner 2017, 2018). We examined two models examining point cross-sectional geometry and penetration depth and two models examining point cross-sectional geometry and wound width. The first pair of models investigates the relationship between TCSA and TCSP and penetration depth with four precision variables (spear mass, thrust number by day to track fatigue, day number to account for skill acquisition, and angle of penetration). The second pair of models investigates the relationship between TCSA and TCSP and wound width with the same precision variables listed above included in the model. All models include a varying intercept that adjusts for the 14 spear types. Models are also distributional to adjust for differential variance across the 14 spear types. We assigned moderately weak prior probability distributions (μ=0, σ=0.1) to all slope values. We used Gaussian distributions for the mean and variance. Sampling was carried out using the No-U-Turn Sampler (NUTS) developed by Hoffman and Gelman (2014). Final models were run with four chains for 10,000 iterations each with a warm-up of 1,000 iterations. For all parameters, r-hat values (a model diagnostic with an expected value equal to one) were exactly one and hence signify model convergence. Chains were inspected visually for sufficient mixing to ensure appropriate model results. The model passes a posterior predictive check, and the residuals are well-behaved. All code and raw data are available here: https://github.com/RobertSWalker/spears.

RESULTS

Tables 3 and 4 and Figure 4 summarize the penetration depths and wound widths for each of the fourteen spear tip types.

Both TCSA and TCSP have strong negative relationships with penetration depth (Table 5). The penetration depth data show that point forms with higher TCSA and TCSP point forms have shallower penetration depths (Figure 5). Of the precision variables, the day is important, suggesting slight improvements in spear thrusting skill throughout the experiment. This model did not find order within the day, angle of thrust, or spear mass to be important. The TCSP model also shows a negative, significant effect of point cross-sectional geometry on penetration depth (Table 6). The precision variables for TCSP had outcomes similar to those of TCSA.

TABLE 4. ENTRY WOUND WIDTH SUMMARY STATISTICS PER SPEAR TYPE.

Spear	Sample size	Mean	Standard deviation	Min	Q1	Median	Q3	Max	Range
1	29	4.46	0.4209	3.0	4.3	4.5	4.7	5.0	2.0
2	29	2.03	0.1583	1.8	1.9	2.0	2.1	2.4	0.6
3	29	2.93	0.1932	2.5	2.8	3.0	3.0	3.3	0.8
4	29	4.54	0.2719	4.0	4.4	4.5	4.7	5.0	1.0
5	29	2.01	0.1559	1.7	1.9	2.0	2.1	2.4	0.7
6	29	3.14	0.2982	2.6	3.0	3.1	3.4	3.9	1.3
7	29	2.61	0.2315	2.1	2.5	2.6	2.7	3.1	1.0
8	11	1.92	0.1348	1.6	1.9	2.0	2.0	2.1	0.5
9	29	4.87	0.3629	4.0	4.7	5.0	5.1	5.5	1.5
10	29	4.91	0.2225	4.5	4.8	4.9	5.0	5.4	0.9
11	29	3.39	0.2186	2.9	3.3	3.4	3.5	3.8	0.9
12	29	3.45	0.3201	3.0	3.3	3.4	3.6	4.7	1.7
13	29	3.33	0.3458	2.6	3.0	3.3	3.6	3.9	1.3
14	29	2.96	0.2622	2.4	2.8	3.0	3.2	3.5	1.1

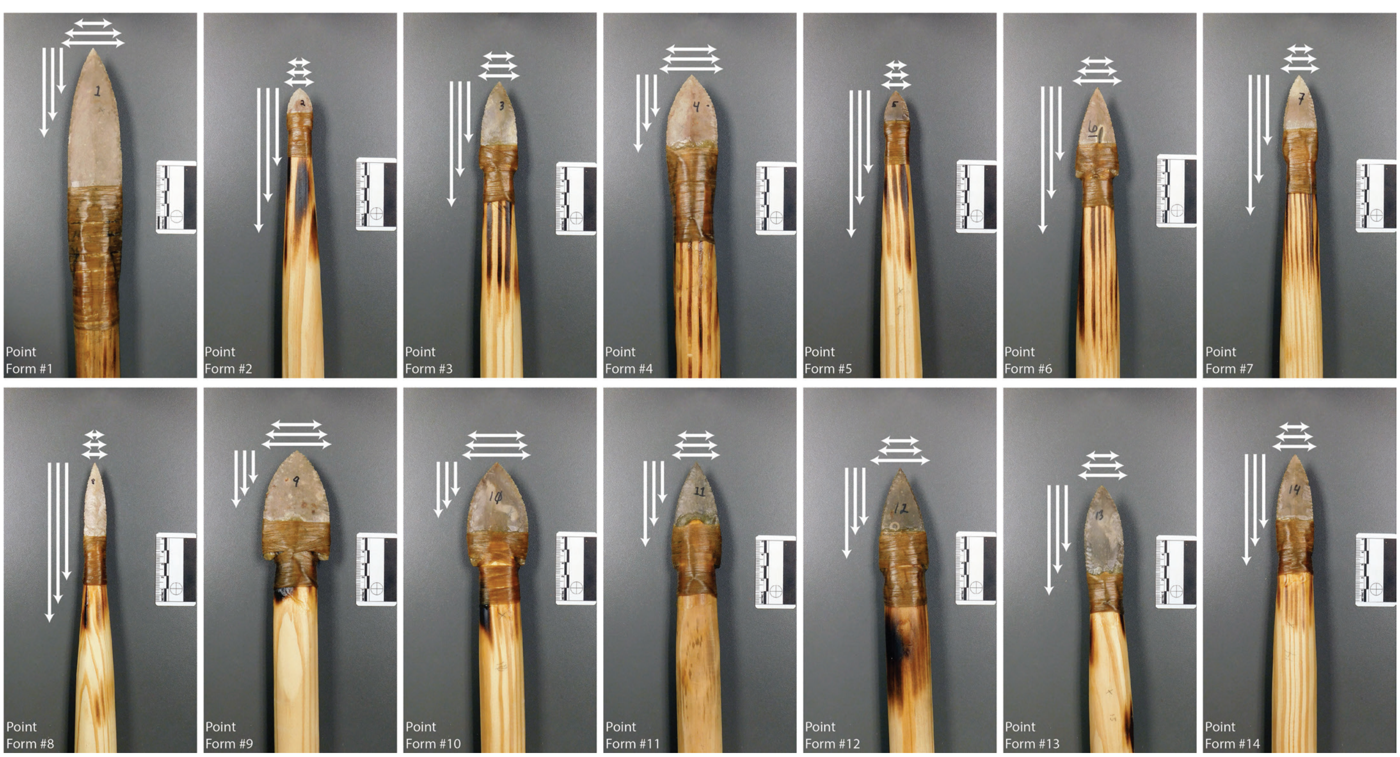

Figure 4. The mean, minimum, and maximum penetration depths and entry wound widths achieved by each spear. The depth values are available in Table 4.

TABLE 5. MULTILEVEL BAYESIAN REGRESSION MODEL OF THE DEPENDENT VARIABLE, PENETRATION DEPTH, WITH TCSA, DAY, ORDER WITHIN DAY, SPEAR MASS, AND ANGLE OF THRUST AS THE INDEPENDENT VARIABLE WITH SPEAR TYPE AS RANDOM INTERCEPT.

		Penetration Depth
Predictors	*Estimates*	*CI (95%)*
Intercept	10.414	4.205 – 16.574
Day	0.409	0.345 – 0.477
Order within day	0.008	-0.001 – 0.016
Spear mass	0.001	-0.008 – 0.009
Angle of thrust	-0.010	-0.020 – 0.000
TCSA	-0.048	-0.065 – -0.032
Random Effects		
σ^2	-0.38	
τ_{00}	5.34	
ICC	-0.08	
N_{spear}	14	
Observations	387	
Marginal R^2 Conditional R^2	0.753 / 0.866	

Next, we examined the relationships between TCSA and TCSP with entry wound width. The wound width data show that point forms with higher TCSA and TCSP values have larger wound widths (Figure 6). The models show that TCSA and TCSP have strong effects on wound width (Tables 7 and 8). Of the precision variables, again the day is important in both models suggesting a slight improvement in spear-thrusting skill throughout the experiment. The other precision variables were not important in either model.

We feel it important to emphasize that although TCSA and TCSP have strong relationships with penetration depth, the relationships are not perfect. Thus, these results suggest that even in controlled experiments there are other aspects of point form, weapon morphology, or propulsion variation that can contribute to penetration depth (e.g., Sitton et al. 2022). For example, as shown in Figure 4, point forms #2 and #5 have somewhat similar penetration depths to point forms #6 and #7, despite each pair possessing different TCSA/TCSP values. Perhaps tip angle is playing a role, or the amount of lashings, or some relationship between point form and hafting, or some other reason, for this patterning.

DISCUSSION

Stone-tipped thrusting spear evolution and function would have directly impacted the survival of ancient humans around the world for hundreds of thousands of years. These implements represent a hafted, composite technology requiring the production and assembly of several materials (Barham 2013). Any of these materials could have potentially influenced the performance of stone-tipped thrusting spears, the failure of which may have on occasion resulted in deadly consequences for their human wielders. Here, we assessed the influence of 14 different stone-tip cross-sectional geometries on two thrusting spear performance variables: penetration depth and entry wound size. Our results showed a clear inverse relationship between TCSA and TCSP and penetration depth—as stone tip geometry became smaller, penetration depth became deeper. Our results also showed a clear positive relationship between TCSA and TCSP and entry wound width—as stone tip geometry became bigger, so too did entry wound width. Together, these results are consistent with the hypothesis that stone tip cross-sectional geometry could have been influenced by the desired performance of Paleolithic people's thrusting spears. In other words, ancient people may have produced and selected different stone-tip cross-sectional geometries at certain times and places depending on their desired thrust-spear functional performance type.

We advocate for our experiments to be repeated, and procedures and variables to be systematically altered (Clarkson et al. 2015; Eren and Meltzer 2024; Eren et al. 2016; Lin et al. 2018). Different types of spears, human participants, thrusting actions, stone tip types (e.g. unifacial, Levallois, stemmed, notched), and thrusting targets are just a few of the possible factors that could be re-tested to help flesh out how much our results are generalizable and whether specific interactions strengthen, weaken, or eliminate the patterns we present above. Importantly, we acknowledge that one variable not held constant among the spears was the "taper" from the wooden shaft to the stone point tip. This taper, which facilitated a smooth transition from stone to wood, may have aided the smaller points'

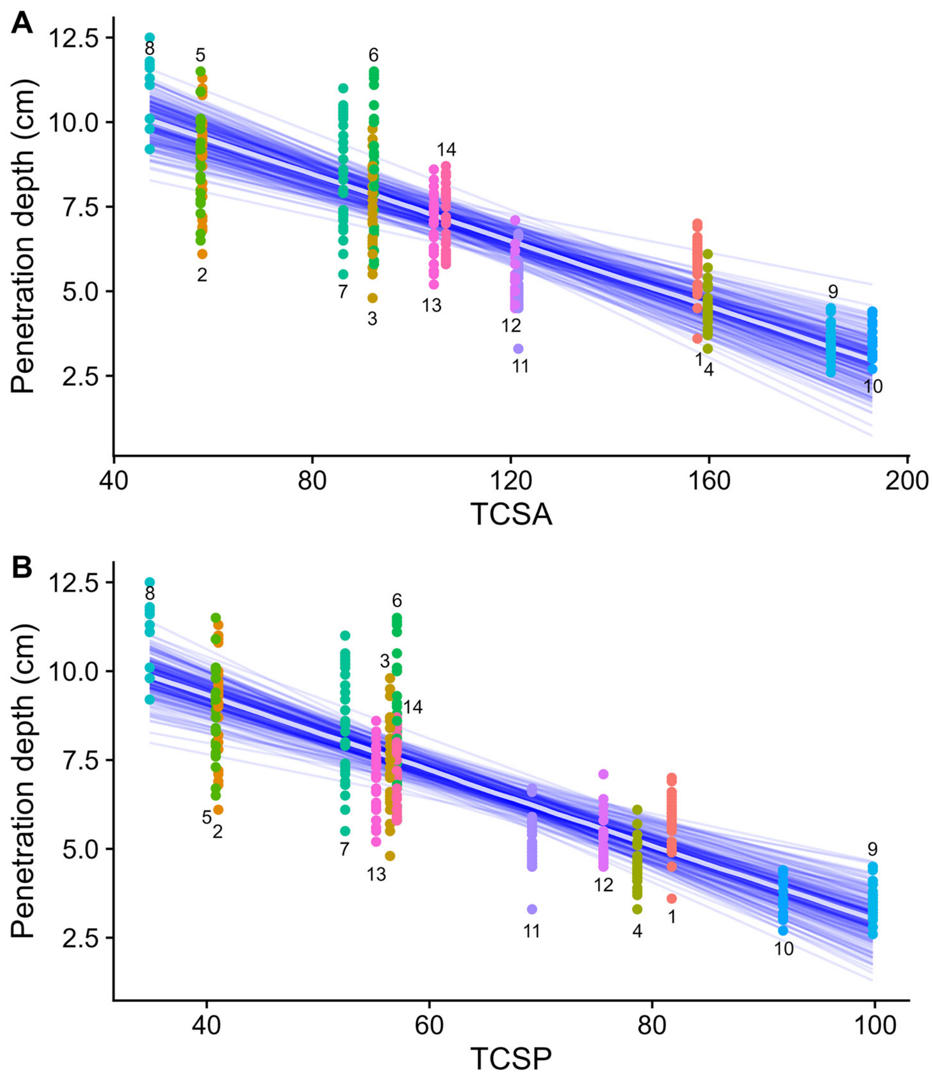

Figure 5. Spaghetti plots with lines representing 200 random draws from the posterior distribution of slopes. Both figures show that increasing A) TCSA (tip cross-sectional area) and B) TCSP (tip cross-sectional perimeter) reduces penetration depth.

penetration relative to the larger points' penetration. However, interestingly, the larger entry wound widths created by larger points did not reduce friction on trailing hafts and shafts by opening a larger hole in the target (Pettigrew and Taylor 2023: 4, 10[4]). Indeed, spears with larger points (e.g., #1, #4, #9, #10, see Figure 4) did not penetrate far enough to reach the lashings or the wooden shaft. These results suggest that there may be a point tip size threshold whereby a point's surface area creates so much initial friction within a target that wooden shaft size becomes moot because penetration to the shaft is never reached. Much more testing is required to support or question this hypothesis.

If we provisionally take our results at face value, the contrasting relationships of penetration depth and entry wound width with stone-tip cross-sectional geometry suggest a functional tradeoff. Plotting spear thrusting penetration depth directly against entry wound width highlights this tradeoff (correlation= -.77 [95% credible interval -.79 to -.74], Figure 7). All else being equal, a stone-tipped thrusting spear can penetrate deeply or create a large entry wound, but not both. Thus, this tradeoff may have influenced when large or small stone-tips would have been employed. Consider a simple, hypothetical example: perhaps an experienced, skilled hunter pursuing an ambush hunting strategy may have selected a small stone tip for his/her thrusting spear, knowing that the chances of targeting and striking a vital organ via deep penetration were high. Alternatively, a less experienced or less skilled hunter without the ability to target a vital organ may have hafted a larger point onto his/her thrusting spear with the understanding that a large entry wound would cause more external damage to at least facilitate tracking via a blood trail.

None of the above is to assert that penetration depth or entry wound width would have been the *only* variables that influenced the evolution and cross-sectional geometry of stone points or to imply that maximizing penetration depth and entry wound width were always predominant considerations of Pleistocene people. For example, tip

TABLE 6. MULTILEVEL BAYESIAN REGRESSION MODEL OF THE DEPENDENT VARIABLE, PENETRATION DEPTH, WITH TCSP, DAY, ORDER WITHIN DAY, SPEAR MASS, AND ANGLE OF THRUST AS THE INDEPENDENT VARIABLE WITH SPEAR TYPE AS RANDOM INTERCEPT.

	Penetration Depth	
Predictors	*Estimates*	*CI (95%)*
Intercept	14.305	8.808 – 19.778
Day	0.410	0.347 – 0.478
Order within day	0.007	-0.001 – 0.016
Spear mass	-0.002	-0.010 – 0.005
Angle of thrust	-0.010	-0.020 – 0.000
TCSP	-0.106	-0.140 – -0.073
Random Effects		
σ^2	-0.36	
τ_{00}	5.32	
ICC	-0.07	
N_{spear}	14	
Observations	387	
Marginal R^2 Conditional R^2	0.762 / 0.865	

durability may have been important in stone point selection (Buchanan and Hamilton 2020; Buchanan et al. 2022; Eren et al. 2022). Although, to our knowledge, the following statement has yet to be robustly tested, larger thrusting spear stone-tips are likely more durable than smaller ones. So, if durability were the target of selection in some contexts, inevitably penetration depth would decrease and entry wound width would increase. Or perhaps in some locations only small raw stone material packages were available—thus, thrusting spear stone-tips would also be unavoidably small, automatically increasing penetration depth while decreasing entry wound width (again, all else being equal). Non-utilitarian functional reasons may have also caused different-sized stone tips to be manufactured as well, for instance, perhaps smaller points were used to transmit social information or larger points were used to intimidate enemies. And, unless a strong contextual case for functional or non-utilitarian functional selection can be made, variation in stone tip cross-sectional areas could always be neutral, arising from cultural drift.

When the results presented here are compared to those of other studies, there are potential implications for weaponry performance and stone tool evolution more broadly. Sitton et al. (2020) investigated the penetration depth of the same 14 stone-tip types we investigated here. However, in the Sitton et al. (2020) study, the stone-tips were 1) hafted onto ~1.27cm diameter, ~71cm long ash shafts 2) with hemp fiber and Kodak gelatin-based glue, and 3) launched at atlatl dart velocities via a compound bow 4) into clay targets. Here, the stone-tips were 1) hafted onto ~3.2cm diameter, ~188cm long pine shafts 2) with thermoplastic adhesive and synthetic sinew, and 3) thrust via a human 4) into ballistics gel targets. Although we could not record kinetic energy in our experiment, Coppe et al. (2019) demonstrate that spear thrusting possesses much higher kinetic energies than projectile technologies. Thus, it seems reasonable to assume that the kinetic energies recorded in Sitton et al. (2020) are likely substantially less than those employed in the present study. Yet, despite these differences between Sitton et al. (2020) and the present study regarding weapon systems, variables, and procedures, both studies recorded the same inverse relative relationship between stone-tip cross-sectional geometry and penetration depth. Together, both results are consistent with the hypothesis that stone-tip cross-sectional geometry contributes to penetration depth regardless of the weapon system. Researchers should look for confounding factors when an experimental study does not reveal the inverse relationship between tip geometry and penetration depth (e.g., Pettigrew et al. 2023; Porta 2019). For example, perhaps the experiment was not conducted blind (leading to conscious or unconscious bias), velocities and kinetic energies were not held constant (or statistically controlled post hoc), shafts or lashings were not held constant, the angle of penetration was not consistent (or, again, statistically controlled post hoc), or weapons were impacting or glancing off bone. With respect to the latter, no reasonable researcher would assume striking, or ricocheting off, bone is the same as striking softer tissues—the inverse relationship between stone-tip TCSA/TCSP and penetration depth only applies currently to softer targets, and when all else is held equal. When all else is not held equal, TCSA/TCSP still contributes to penetration depth variation, but its contribution may or may not be overwhelmed by other factors (Eren and Meltzer 2024; Paige et

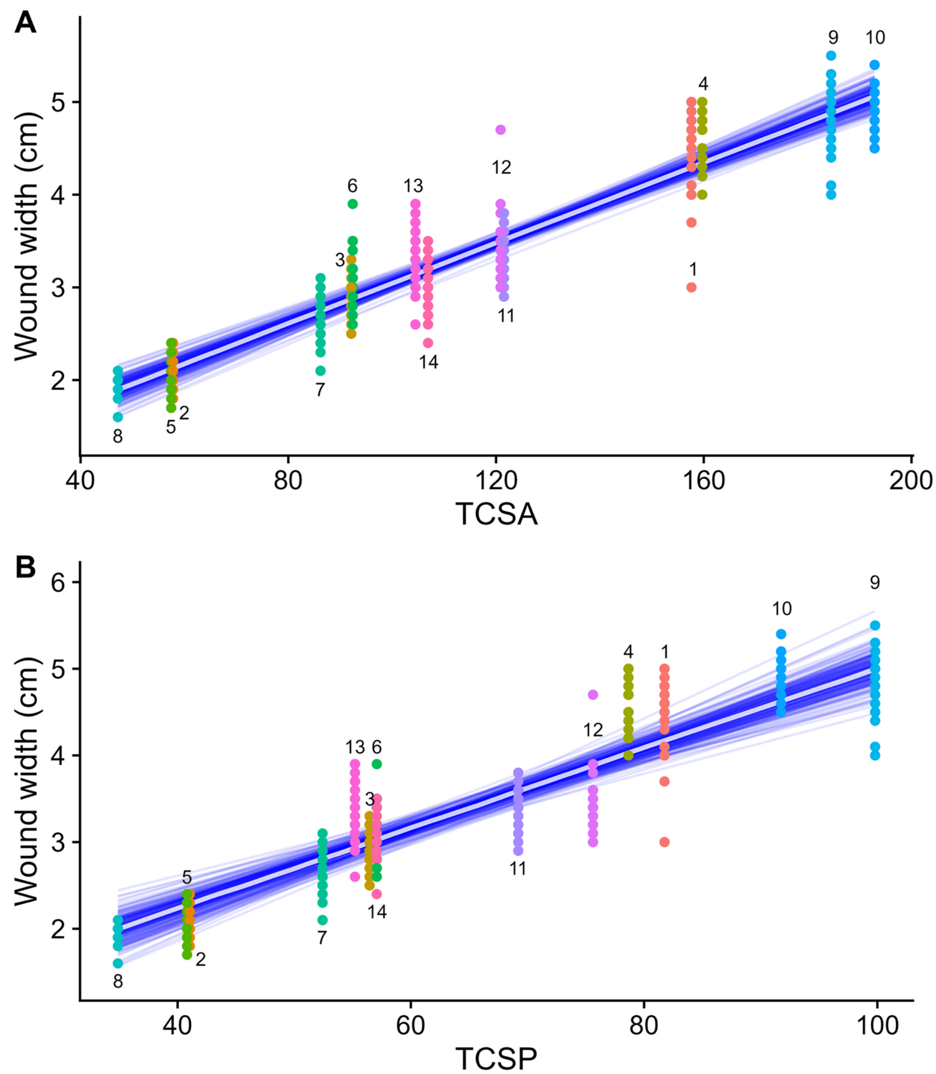

Figure 6. Spaghetti plots with lines representing 200 random draws from the posterior distribution of slopes. Both figures show that increasing A) TCSA (tip cross-sectional area) and B) TCSP (tip cross-sectional perimeter) increases wound width.

al. in press; Sitton et al. 2023). Additionally, more powerful statistics or larger sample sizes may be necessary to tease out the TCSA/TCSP contribution to penetration depth in less controlled experiments where there is increased variable interaction and thus much more "noise" in the data (compare Eren and Meltzer 2024 and Paige et al. in press with Pettigrew et al. 2023).

While the *relative* results of Sitton et al. (2020) and the present study are consistent, the experimental variable and protocol differences between the two studies precludes a meaningful direct comparison of the *absolute* results. For example, if a point type penetrated more deeply in the Sitton et al. (2020) study than it did in the current study, is that due to the target substrate, the propulsion/thrust mode, the shaft/hafting materials, or some combination of all these variables? We cannot currently say.

Finally, to be clear, here we assessed TCSA/TCSP in terms of how these variables potentially influenced relative performance within a single weapon system (i.e., the thrusting spear). However, others have attempted to use TCSA/TCSP to infer the specific weapon system(s) used by past peoples (i.e., the thrusting spear, the javelin, the atlatl and dart, the bow and arrow). We do not currently support the latter practice. Even at "broad-trends" (Lombard et al. 2024) and "course-grained" (Lombard 2021: 14) levels or when using "large-samples" (Lombard and Moncel 2023: 3)—all practices we strongly and regularly advocate (see also Wilkins et al. 2015)—attempting to infer the weapon system(s) from stone point cross-sectional geometry is fraught with confounds, equifinality, unsupported assumptions, or problematic ethnographic or experimental reference models (e.g., see discussions in Clarkson 2016; Conrad et al. 2023; Hutchings 2016; Leder and Milks 2025; Milks et al. 2024; Newman and Moore 2013; Rots and Plisson 2014; Sahle et al. 2023)[5]. Given all the possible pitfalls of using TCSA/TCSP for inferring weapon systems, the notion that

TABLE 7. MULTILEVEL BAYESIAN REGRESSION MODEL OF THE DEPENDENT VARIABLE, ENTRY WOUND WIDTH, WITH TCSA, DAY, ORDER WITHIN DAY, SPEAR MASS, AND ANGLE OF THRUST AS THE INDEPENDENT VARIABLE WITH SPEAR TYPE AS RANDOM INTERCEPT.

	Entry Wound Width	
Predictors	*Estimates*	*CI (95%)*
Intercept	0.489	-0.556 – 1.522
Day	0.048	0.024 – 0.071
Order within day	-0.002	-0.004 – 0.001
Spear mass	0.000	-0.001 – 0.002
Angle of thrust	0.000	-0.003 – 0.004
TCSA	0.022	0.019 – 0.024
Random Effects		
σ^2	-0.89	
τ_{00}	1.92	
ICC	-0.87	
N_{spear}	14	
Observations	388	
Marginal R^2 Conditional R^2	0.908 / 0.928	

TABLE 8. MULTILEVEL BAYESIAN REGRESSION MODEL OF THE DEPENDENT VARIABLE, ENTRY WOUND WIDTH, WITH TCSP, DAY, ORDER WITHIN DAY, SPEAR MASS, AND ANGLE OF THRUST AS THE INDEPENDENT VARIABLE WITH SPEAR TYPE AS RANDOM INTERCEPT.

	Entry Wound Width	
Predictors	*Estimates*	*CI (95%)*
Intercept	-1.263	-2.748 – 0.236
Day	0.048	0.024 – 0.072
Order within day	-0.002	-0.000 – 0.004
Spear mass	0.002	-0.000 – 0.004
Angle of thrust	0.000	-0.003 – 0.004
TCSP	0.047	0.037 – 0.056
Random Effects		
σ^2	-0.86	
τ_{00}	1.89	
ICC	-0.84	
N_{spear}	14	
Observations	388	
Marginal R^2 Conditional R^2	0.878 / 0.928	

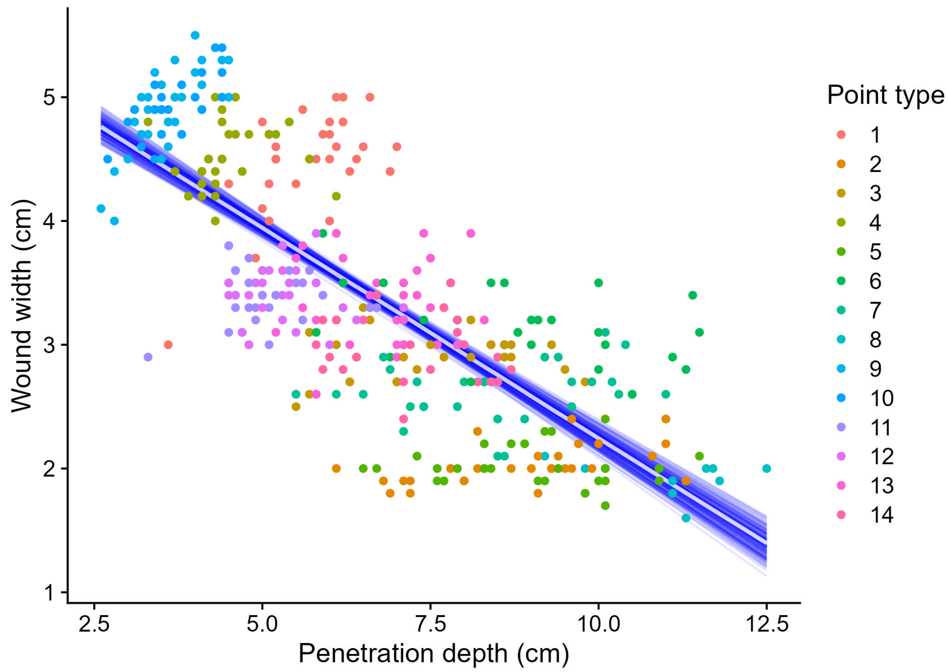

Figure 7. Tradeoff between penetration depth and entry wound width. Lines represent 200 random draws from the posterior distribution of the slope.

TCSA/TCSP is merely an "instrument for building… testable hypotheses" (Lombard et al. 2024: 45) cannot presently be sustained. A researcher could just as easily speculate about weapon systems without reference to TCSA/TCSP—after all, only four systems are usually in question—and test that hypothesis with "use-trace, experimental, or faunal data" (Lombard et al. 2024). The advantage of the latter approach is that there is no chimerical empirical or quantitative foundation. In other words, given how problematic TCSA/TCSP is for inferring weapon systems, it cannot yet reliably serve as a way "to generate hypotheses about intra- and inter-site weapon use on a regional or a global scale" (Lombard and Moncel 2023: 17).

ENDNOTES

[1]However, as Biermann Gürbüz and Lycett (2020) point out, it is worth remembering that "hunting *without* the use of tools has now long been identified in our sister genus *Pan" (emphasis added).*

[2]Our focus in this study is on thrusting spears (also known as "lances," Gaudzinski-Windheuser 2016: 78), but we acknowledge that early spears also may have been thrown akin to javelins (Churchill 1993; Lynch 2023; Hitchcock and Bleed 1997; Iovita et al. 2014; Milks 2018; Milks et al. 2019; Porta 2019; Sahle et al. 2013).

[3]Following others (Iovita et al. 2014; 2016; Lynch 2023: 251; Milks et al. 2016; see also Porta 2019), we agree that the use of projectile technology (e.g., calibrated cross bows) is likely not suitable for experiments that explicitly wish to investigate spear thrusting. Nor can impact velocity and spear mass alone be used to calculate the kinetic energy of a spear thrust (compare Coppe et al. 2019 vs. Smith et al. 2020). As Milks et al. (2016: 198) note, "Thrusting spears remain in the hand in use, and therefore are not projectile weapons (Hughes 1998; Hutchings 2011). Their mechanics differ from those of projectiles, and this should be reflected in how they are replicated in experimental work. A person using a thrusting spear literally puts their body mass behind the weapon." Milks et al. (2016: 198–199) go on to state that "firing a spear as a projectile, for example by crossbow or air-cannon, can mimic impact velocities, but not the changes to momentum in the thrusting action *after* initial impact (Hutchings 2011; Iovita et al. 2016; Sano et al. 2016)" (emphasis added).

[4]We fully acknowledge that Pettigrew and Taylor (2023) were examining leather armor, not only target simulants, when making this statement. We are not questioning their results. However, much more research is needed on the relationship between entry wound size and penetration depth before any firm or broad conclusions are drawn with respect to one target medium (tissue simulant), or any combination of target mediums (armor + tissue simulant, hair + tissue simulant, etc.).

[5]An essential part of the TCSA/TCSP argument in using these metrics to hypothesize a weapon system is based on the idea that a point should be larger than the shaft to allow sufficient penetration to kill an animal by blood loss. For example, Hughes (1998: 353) states: "If the tip is designed to open a hole large enough for the shaft to enter unimpeded, then the tip cross-sectional area must be larger than the shaft area." We note, however, that if larger points preclude, or reduce the chances that, the shaft is reached—as our results show (see Figure 4 and the second paragraph in the Discussion section)—then Hughes' (1998) idea, and the automatic relationship between point size, shaft size, and weapon system, is further questioned.

ACKNOWLEDGEMENTS

This research was financially supported by the National Science Foundation (NSF, Awards 1649395 and 1649406), and the Kent State University College of Arts and Sciences. We are appreciative to Karen Ruebens, Justin Pargeter, Justin Coppe, and an anonymous reviewer who provided valuable comments on our manuscript that improved it.

DATA AVAILABILITY AND PERMITS

All raw data and code can be found here: https://github.com/RobertSWalker/spears.

AUTHOR CONTRIBUTIONS

Conceptualization: M.I.E., B.B., B.S., J.P.; Methodology: M.W., M.R.B., M.I.E.; Formal Analysis: B.B., R.S.W.; Investigation: S.M., J.T., J.B.; Writing—Original Draft: M.I.E., B.B., R.S.W.; Writing—Review and Editing: all authors; Supervision: M.I.E., M.R.B.; Project Administration: M.I.E.; Funding Acquisition: B.B., B.S., M.R.B., M.I.E.

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