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Projectile point morphology and penetration performance

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ABSTRACT

Prehistoric pointed lithic armatures (used to tip spears, darts, and arrows) vary considerably in mechanically-relevant aspects of their morphology, such as tip cross-sectional shape, cross-sectional perimeter, and cross-sectional area, mechanical advantage, and edge sharpness. The effect of variation in these parameters on penetration performance and lethality, however, is poorly understood. Six 3D-printed points that varied in cross-sectional shape, tip cross-sectional area, tip cross-sectional perimeter, mechanical advantage, and edge sharpness were fired into ballistic gelatin under controlled conditions to evaluate the importance of these variables on point performance. Tip cross-sectional perimeter was found to have the greatest effect on penetration depth in the gelatin, and mechanical advantage was also significantly related to penetration. Cross-sectional shape and tip cross-sectional area were not significantly related to penetration depth, while edge sharpness inversely affected penetration. These results highlight the importance of tip cross-sectional perimeter in the evolution of projectile point design (and reinforce its utility as an indicator of long-range projectile weaponry in the archeological record), but also underscore the multiple constraints that interact when trying to design points to maximize penetration performance, lethality, and durability.

1. Introduction

Mechanically-relevant features of pointed lithics have increasingly become the focus of efforts to identify early long-range projectile weapons in the archeological record, and to understand the performance factors that guided the evolution of projectile point morphology over the course of prehistory. Lithic tips on arrows and spear-thrower darts serve as the forward end of projectiles that must both fly some distance through a fluid medium while maintaining flight stability and accuracy on target, and convert momentum to penetration depth and tissue damage upon striking the target. Under the assumption that mechanically-relevant properties that enhance projectile flight stability and lethality were the foci of the technological development of projectile armatures (Hughes, 1998), several such properties have been proposed as important for understanding the evolution of projectile technology and for identifying and differentiating prehistoric projectile systems (e.g., spear-thrower from bow) based on the morphology of lithic points (Hughes, 1998; Brooks et al., 2006; Shea, 2006; Sisk and Shea, 2009). Despite considerable recent experimental work on point morphology and performance (e.g., Waguespack et al., 2009; Wilkins et al., 2014; Salem and Churchill, 2016; Sitton et al., 2020; Buchanan et al., 2022), it remains uncertain how properties such as tip angle, tip cross-sectional area, tip cross-sectional perimeter, edge mechanical advantage, and edge sharpness relate to the penetration performance and lethality of stone-tipped weapons.

Two mechanically-relevant properties in particular – tip cross-sectional area and tip cross-sectional perimeter – have received the most attention in studies of projectile point technology. According to Hughes (1998), tip cross-sectional area is directly proportional to the drag experienced as a point passes through tissue, and thus inversely proportional to penetration depth (since points contribute only about 4% of the aerodynamic drag experienced by an arrow [Park, 2011], and since aerodynamic drag is relatively negligible over the short distances [ca. 25 m on average: Churchill, 1993] that arrows are fired at prey by historically-known foragers [velocity losses average ca. 5% over 25 m: see Park, 2011], we focus here on the behavior of points upon contacting prey). Mechanically-launched weapons (spear-thrower dart and arrow) tend to operate at lower kinetic energy (KE) and momentum (p) than hand-delivered weapons (thrusting and throwing spears) (Hughes, 1998; Coppe et al., 2019), and must thus employ smaller armatures that

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maximize stress on impacted tissues and that experience less drag. Consequently, Hughes (1998) documented a decrease in average tip cross-sectional area along a decreasing momentum continuum from thrusting spears to throwing spears to spear-thrower darts to arrows. Sisk and Shea (2009), however, found that tip cross-sectional perimeter was a better predictor of penetration depth than tip cross-sectional area in experiments using lithic-tipped arrows fired at archery targets and simulated animal carcasses (see also Sitton et al., 2020). These authors (Sisk and Shea, 2011) have also suggested that tip cross-sectional perimeter may be a more sensitive variable by which to detect the earliest emergence of mechanically-propelled weapons in the Paleolithic record.

If tip cross-sectional area is inversely proportional to drag, how does tip cross-sectional perimeter relate to penetration performance? Unlike high-velocity firearm rounds that cause extreme compression of tissues and large cavitation effects (Mendelson, 1991), dart tips and arrowheads employ greater mass at comparatively lower velocity to slice through tissues (Ashby, 2000). To maximize penetration depth and the size of the wound channel (see Wilkins et al., 2014; Salem and Churchill, 2016), a projectile must overcome drag forces exerted by the tissues it is encountering. Objects moving through fluid media experience both form and skin surface drag (Sadraey, 2009). Form drag is caused by the resistance of the medium to displacement, and is proportional to the cross-sectional area of the object normal to the direction of motion (Sadraey, 2009), or in the case of a projectile point, tip cross-sectional area. Skin surface drag is the friction that develops as an object and a medium move past one another in opposite directions, and is proportional to the total surface area (often called the “wetted” surface area) in contact with the medium (Sadraey, 2009). In the case of a projectile point passing through animal tissue, the wetted surface area would be that of the faces of the point (that is, minus the proximal surface area of the base). For points with both triangular and quadrilateral cross-sections (see Sisk and Shea, 2011), the wetted surface area is ≈ tip cross-sectional perimeter * length/2. Thus, the relative importance of tip cross-sectional area and tip cross-sectional perimeter to projectile penetration is likely to be a function of which of these two forms of drag is most important in terms of resisting penetration. However, while animal soft tissues have an average mass density roughly equal to that of water (Katch et al., 1967), the presence of collagen, cell membranes, peptide chains, glycopeptides, and other elastic materials cause these tissues to maintain a semi-solid structure (Odian, 1991; Shadwick, 1998). Breaking molecular bonds in animal tissues uses considerable momentum, and, given their elastic nature, requires more force to break than rigid strands (Odian, 1991). Increasing the cutting efficiency of a point can drastically reduce the amount of resistance experienced by the arrow (Ashby, 2000), so much so that the addition of even a few microliths to antler points (adding sharp edges without significantly altering point cross-sectional area) has been shown to almost double their penetration ability in animal carcasses (Pétillon et al., 2011; see also Wood and Fitzhugh, 2018). In addition to enhancing hemorrhaging in prey (Friis-Hansen, 1990), sharp edges are more efficient at breaking molecular bonds in the tissues through which they are slicing, since the applied force (parallel to the cutting edge) is acting on a smaller volume of tissue. For lithic points, cutting efficiency can be improved by enhancing both the mechanical advantage of the point (Ashby, 2000) and the sharpness of the cutting edges (Friis-Hansen, 1990). Bifacial and unifacial points possess two cutting edges that function as inclined planes which use the force exerted by the projectile on the target (as the projectile decelerates) to perform the work of cutting and displacing tissue. The mechanical advantage of a point is the “run-to-rise” ratio of the cutting edge from the tip distally to the shoulder proximally, and is thus proportional to point length and inversely proportional to width (Ashby, 2000). While a low tip angle (or front angle) has also been identified as important to projectile penetration (Friis-Hansen, 1990), for most points tip angle is simply an inverse measure of mechanical advantage. Edge sharpness is inversely proportional to the angle at which the dorsal and ventral surfaces of the point meet at the cutting edge (Hainsworth et al., 2008).

Teasing apart the functional importance of tip cross-sectional area, tip cross-sectional perimeter, mechanical advantage, and edge sharpness is made difficult by the fact that they all covary with point width, and that the length, width, and thickness of a point interact in functional ways beyond their role in penetrating tissue (Buchanan and Hamilton, 2020). For instance, while mechanical advantage can be enhanced by lengthening a point, this creates durability issues because stone is brittle (i.e., it does not absorb much energy before breaking) despite its high compressive strength (Cheshier and Kelly, 2006). To maintain reasonable durability, a lithic point must have a thickness to length ratio greater than 0.121 (Cheshier and Kelly, 2006), such that increasing mechanical advantage by lengthening a point requires increasing the point’s thickness to maintain durability – which is likely to have a disproportionate effect on tip cross-sectional area (Sisk and Shea, 2009) and will also decrease edge sharpness. Alternatively, mechanical advantage can be enhanced by decreasing the width of the base, which disproportionately decreases tip cross-sectional perimeter (Sisk and Shea, 2009) and edge sharpness, especially if thickness is held constant in order to maintain point durability. Thus, the empirical finding that tip cross-sectional perimeter is a better predictor than tip cross-sectional area of a point’s penetrating ability (Sisk and Shea, 2009) may have more to do with the relationship of this variable to mechanical advantage than with its functional role in skin surface drag during penetration. Additionally, the cross-sectional shape of a point may affect its mechanical performance. Unifacial points with a markedly triangular cross-sectional shape may present a third, relatively dull edge along the midline of the point. Thus, for a given length and tip cross-sectional area or tip cross-sectional perimeter, points with a triangular cross-section (hereafter “triangular points”) may have reduced mechanical advantage compared to bifacial points with a rhomboidal cross-section (hereafter, “rhomboidal points”), since mechanical advantage is inversely proportional to the number of cutting edges on the point (Ashby, 2000). This aspect of cross-sectional shape may explain a prehistoric preference for tipping mechanically-propelled projectiles with rhomboidal bifaces (Sisk and Shea, 2009). The mechanical relevance of these morphological properties – tip cross-sectional area, tip cross-sectional perimeter, mechanical advantage, edge sharpness, and cross-sectional shape – remains unclear.

2. Materials and methods

To better understand the functional importance of tip cross-sectional area, tip cross-sectional perimeter, mechanical advantage, and edge sharpness, as well as overall cross-sectional shape (triangular vs. rhomboidal) on penetration performance, six points of varying dimensions (Table 1) were designed using the CAD program SolidWorks 2016®, and printed on a Zortrax® M200 3D printer using 0.14 mm plastic Z-HIPS (High Impact Polystyrene) Filament (Fig. 1). While the material properties of polystyrene differ in important ways from those of the silicates from which lithic points are usually produced, by designing and 3D-printing our own points we were able to compare the penetration performance of pairs of points which had identical (or nearly identical) tip cross-sectional area but which differed in tip cross-sectional perimeter, and vice-versa (which would not be possible with knapped bifaces, in which tip cross-sectional area and perimeter tend to co-vary: see below). Z-HIPS is a hard polystyrene that produces smooth printed surfaces, and while it is about an order of magnitude more elastic under both tension and compression than stone (unfortunately, material testing conducted on lithic raw materials [e.g., Domanski et al., 1994] tends to focus on mechanical properties involving compression, while testing of 3D printing materials tends to focus on mechanical properties under tension and flexion [see for example https://cf.zortrax.com/wp-content/uploads/2019/01/Z-HIPS_Technical_Data_Sheet_eng.pdf], making direct comparison of the two types of material difficult), it

Table 1
Dimensions of points used in the experiment.

Point	Length (cm)[a]	Width (cm)[a]	Thickness (cm)[a]	TCSA (cm^2)[b]	TCSP (cm)[b]	Surface Area (cm^2)[a]	Edge length (cm)[c]	MA[d]	ES[e]
Rhomboid 1	6.00	3.18	3.18	5.06	9.00	26.98	6.12	0.96	63.7
Rhomboid 2	6.00	5.25	1.93	5.06	11.18	33.56	6.55	1.25	141.9
Rhomboid 3	6.00	4.00	2.06	4.12	9.00	27.00	6.32	1.58	105.1
Triangle 1	6.01	5.19	1.50	3.89	11.18	33.60	6.24	1.20	190.8
Triangle 2	5.99	3.00	2.60	3.90	9.00	26.96	6.58	2.19	95.5
Triangle 3	6.00	4.16	1.25	2.60	9.01	27.04	6.38	1.53	184.8

[a] Dimension measured *in silico* using CAD program. Width and thickness taken at base.

[b] Tip cross-sectional area (TCSA) and tip cross-sectional perimeter (TCSP). Dimensions calculated using base width and thickness, using formulae for rhomboidal and triangular points from Sisk and Shea, 2011.

[c] Length of a single cutting edge (CEL), as measured *in silico* using CAD program.

[d] Mechanical advantage (MA) following Ashby, 2000. For Rhomboid 1 (which has a square rather than rhomboidal base shape, and thus four cutting edges), MA calculated as (CEL/Width)/2; for all other points (with two cutting edges each), MA calculated as CEL/Width.

[e] Edge sharpness (ES) index, calculated as $100(1/\theta)$, where θ = edge angle in radians. θ was calculated from width (w) and thickness (t) as $2(\arctan([t/2]/[w/2]))$ for rhomboidal points and as $\arctan([t/2]/[w/2])$ for triangular points.

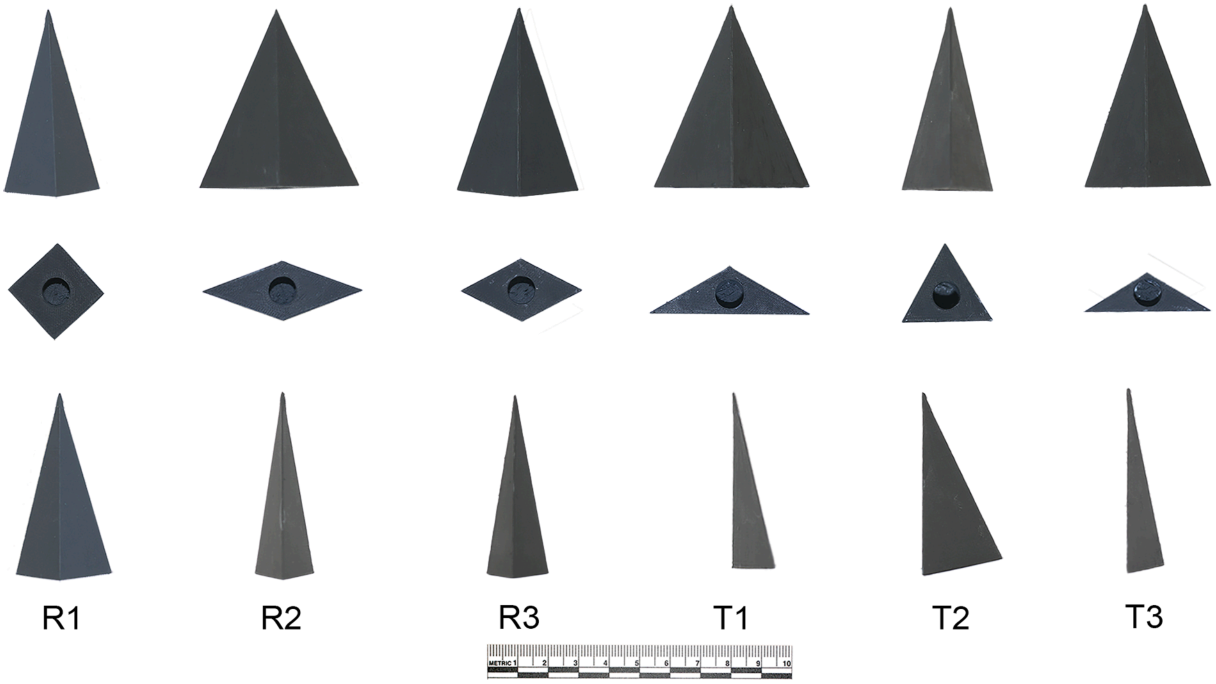

Fig. 1. 3D-printed projectile points used in the penetration experiment. Dimensions of rhomboidal (R1-R3) and triangular (T1-T3) points are provided in Table 1. Points are shown in anterior (top row), basal (middle), and lateral (bottom) perspectives. Scale in centimeters.

is a relatively hard, stiff, and tough polymer capable of repeated firings into ballistic gelatin without suffering plastic deformation. It is not clear what, if any, effect differences in material properties between polystyrene and stone have on penetration performance in ballistic gelatin, but given that all of the points used in this study were made of polystyrene, it is likely that performance differences between points were a function of differences in their mechanically-relevant morphology (tip cross-sectional area, tip cross-sectional perimeter, mechanical advantage, and edge sharpness).

Three triangular and three rhomboidal points were used to test for penetration performance differences between points with different base shapes. While the rhomboidal points tend to have larger tip cross-sectional areas than the triangular points (Table 1), we were able to create one pair of points (Rhomboid 3 and Triangle 2 in Table 1) with roughly equal tip cross-sectional area and identical tip cross-sectional perimeters. To test for the relative importance of tip cross-sectional area vs. tip cross-sectional perimeter, each shape group was designed to contain two sets of points; one set with the same tip cross-sectional area but different tip cross-sectional perimeters, and another set with the same tip cross-sectional perimeter but different tip cross-sectional areas (Table 1). Mechanical advantage overlapped between the two shape groups, and ranged from 0.96 to 2.19 (Table 1). In calculating mechanical advantage we considered the triangular points to have two cutting edges (see Table 1), although we also examined the effect of mechanical advantage on point performance when mechanical advantage was calculated under the assumption that triangular points possess three cutting edges.

Each point was standardized to a mass of 12.28 g, and was fitted to a carbon fiber bolt with a mass of 21.5 g (Fig. 2). The total length of the points and shafts were standardized to 62.4 ± 0.2 cm. Mounted points were fired into ballistic gelatin using a 27.2 kg (60 lb) draw-weight crossbow (Barnett® Phantom Jr.), fired from a bench rest at a distance of 65 cm (sufficient to allow the bolt to completely clear the string prior to striking the gel). Repeated trials ($n = 9$) using a dummy bolt of identical mass to the test bolts, fired through a Shooting Chrony® F-1 chronograph, revealed an average bolt velocity of 34.54 ± 1.32 ms^{-1}.

Ballistic gelatin (professional grade 10% calibrated VYSE®) was prepared following Jussila (2004), and poured into 36 cm × 21 cm × 12

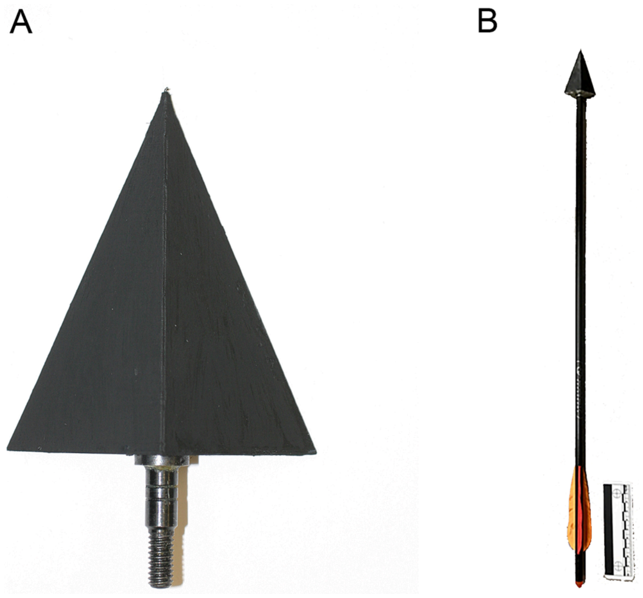

Fig. 2. (A) Detail of projectile point fitted with mounting hardware; (B) projectile point mounted to bolt for firing (scale in centimeters).

cm molds to create the test blocks. Blocks were refrigerated at 4 °C for over 24 h. Three (14%) of the blocks were randomly selected (using Randomizer 3.2 for iPhone) for calibration testing. Calibration was conducted by firing a 0.177 caliber (4.5 mm) pellet at an average velocity of 186.08 ± 0.22 ms^{-1} (as measured by chronograph) from a Crosman® model 2100 air rifle. Average pellet penetration depth (93 ± 1 mm) was judged (using regression equations in Jussila, 2004) to be within the acceptable standards for ballistic gel. For the gel to maintain correct density for the experiment, each block was used within 20 min of being removed from the refrigerator.

During testing points were selected at random (using Randomizer 3.2 for iPhone), and sprayed with PAM® cooking spray on all sides and on the shaft to reduce the coefficient of friction (and thus mimic blood lubrication) prior to firing. Four shots were fired into each block, and penetration depth and intra-block firing order were recorded (the latter to test for firing order effects on penetration depth, which was found to be insignificant). After firing, the shaft of the bolt was marked at the surface of the gel block before removal, and penetration depth was measured from this mark to the point tip. Initially nine trials were conducted with each point. Preliminary examination of the data revealed a greater range of penetration depths for one point (R1, whose depths varied over a range of 1.9 cm) relative to the five other points (mean depth range = 0.8 ± 0.2 cm), which raised the possibility of a problem with the hafting of this point (laxity in the haft could potentially lead to variation in the angle at which the point penetrated the gel). Thus, point R1 was refit and recalibrated, and fired nine additional times into gel blocks. The two sets of trials produced nearly identical mean penetration depths (13.47 vs. 13.44 cm) but different standard deviations (0.61 vs. 0.30). Given that greater variance decreases the probability of rejecting the null hypothesis (no effect of tip cross-sectional area, tip cross-sectional perimeter, mechanical advantage, or edge sharpness), we considered it to be conservative to pool the two sets of trials for further analysis. After retesting point R1, sufficient gel blocks remained to allow an additional three trials for each of the other five points. For two of the trials with points R2, R3, and T1 and one trial for point T2 there was evidence of loosening of the haft during penetration (indicated by detachment of the hafting material or displacement of the metal shot used to standardize point weight): these trials were excluded from the analysis. All statistical analyses were conducted in JMP® 13.0.0 (JMP, 1989–2019).

Experimental and actualistic studies of projectile point performance usually employ lithic or bone points fired into animal carcasses (e.g., Guthrie, 1983; Sisk and Shea, 2009), clay (Sitton et al., 2020), ballistic gelatin (e.g., Wilkins et al., 2014; Salem and Churchill, 2016; Wood and Fitzhugh, 2018), or come combination of ballistic gelatin and animal tissues (e.g., Waguespack et al., 2009). These studies vary in the extent to which they control for extraneous variables, and in their merits and limitations. We recognize that firing large polystyrene points into ballistic gelatin in a laboratory is a far cry from the realities of hunting prey with lithic or osseous points affixed to darts or arrows. In particular, a few key constraints of this study limit its generalizability to real-world hunting in the Pleistocene and Holocene: (1) while our study design allows us to examine the effect of edge sharpness in a general sense (that is, as defined by the angle at which the ventral and dorsal faces of the point meet), the edges on the 3D-printed points are relatively dull compared to those that can be produced on silicates; (2) ballistic gelatin is brittle while muscle and skin are tough, such that edge sharpness may be much more important to point performance in animal tissues (see Discussion), and; (3) animal targets present hard tissues (bones) that may serve to hinder point penetration, and it is possible that some mechanically-relevant variables that appear to be unimportant to penetration in ballistic gelatin may play a role in passing through bony obstacles in animal targets. Thus, the results presented here should be seen as adding to our understanding of the ways in which points interact with the semi-solid tissues through which they pass, but should not be expected to provide a complete picture of the mechanical and functional relevance of point morphology as realized in prehistoric hunting.

3. Results

Mean penetration depths by point type are presented in Table 2. As an initial step in the analysis, we tested for differences in penetration performance between rhomboidal (R) and triangular (T) points with two two-tailed t-tests (all R vs. all T; R vs. T holding both tip cross-sectional area and tip cross-sectional perimeter constant (roughly) [R3 vs. T2]). This step was undertaken to determine if the two point shapes could be pooled for further analysis, thus no correction was made for the elevated family-wide type I error rate that occurs with multiple tests (Rice, 1989), increasing (conservatively) the probability of rejecting the null hypothesis of no difference between point shapes. We found no difference between overall cross-sectional shape ($\overline{X}_T = 12.8 \pm 1.4$ cm, $\overline{X}_R = 13.0 \pm 1.2$ cm; t = 0.3807, df = 69, p = 0.7046) or between shape types when tip cross-sectional area and tip cross-sectional perimeter were held constant (t = 1.8206, df = 15, p = 0.0887), and thus the two point shapes were pooled for further analysis.

Regression analysis (Fig. 3) reveals that tip cross-sectional area is insignificantly related to penetration depth (F(1, 69) = 1.9519, p = 0.1669), and that variation in tip cross-sectional area accounts for less than three percent of the variation in penetration depth ($r^2 = 0.0275$). Tip cross-sectional perimeter, on the other hand, was significantly related to penetration performance (F(1, 69) = 524.9363, $p < 0.001$), with variation in tip cross-sectional perimeter accounting for more than

Table 2
Mean penetration depth (±SD) and total volume tissue damage of experimental projectile points.

	N[a]	Mean Penetration Depth (cm)	TVTD (cm^3)[b]
Rhomboid 1	18	13.5 ± 0.47	68.3
Rhomboid 2	10	11.2 ± 0.21	56.7
Rhomboid 3	10	13.9 ± 0.21	57.3
Triangle 1	10	10.9 ± 0.27	42.4
Triangle 2	11	14.1 ± 0.42	55.0
Triangle 3	12	13.3 ± 0.29	34.6

a. Number of shots.
b. Total volume tissue damage (TVTD), or wound channel size, = tip cross-sectional area *mean penetration depth, following Salem and Churchill (2016).

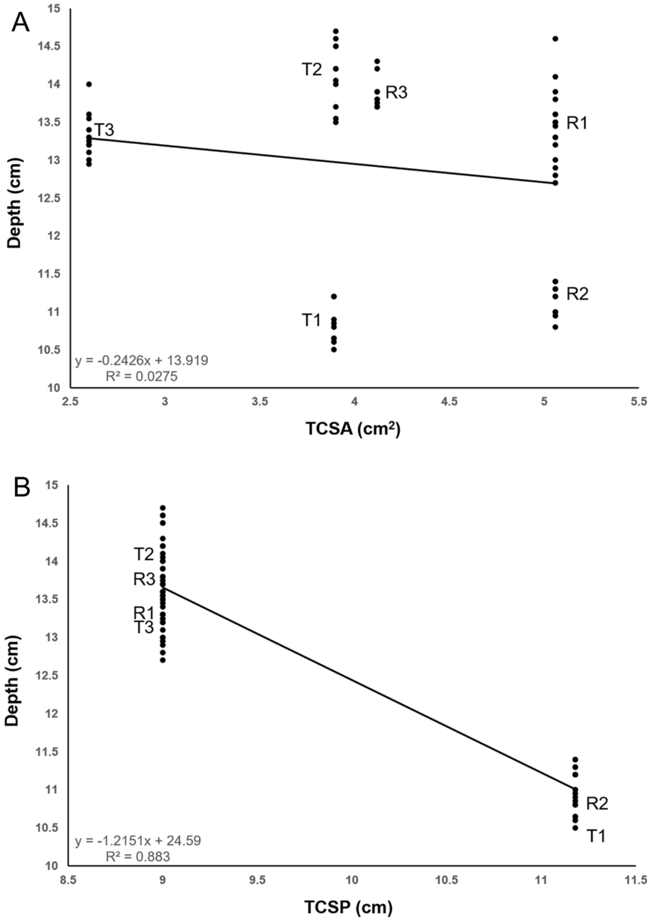

Fig. 3. Scatter plots of penetration depth (cm) versus (A) tip cross-sectional area (TCSA: cm^2) and (B) tip cross-sectional perimeter (TCSP: cm). Experimental point identifiers (see text) are provided adjacent to each cluster of data points. Lines and equations are from ordinary least squares regressions.

88% of the variation in penetration depth ($r^2 = 0.883$). Penetration depth decreased by 1.22 cm for every one-centimeter increase in tip cross-sectional perimeter ($y = -1.215x + 24.59$). To further test the effect of tip cross-sectional area on penetration depth, we conducted a one-way analysis of variance (ANOVA) on points R1, R3, T2, and T3 (which all have a tip cross-sectional perimeter of 9.0 cm but which vary in tip cross-sectional area between 2.6 cm^2 and 5.1 cm^2: Table 1), as well as a two-tailed *t*-test on points R2 and T1 (both with tip cross-sectional perimeters of 11.2 cm but with tip cross-sectional areas of 5.1 and 3.9 cm^2, respectively: Table 1). The ANOVA detected significant differences between groups ($F = 11.6438$, $df = 3$, $p < 0.001$), and post-hoc testing (Tukey-Kramer HSD) revealed that points R3 and T2 did not differ from one another, nor did points R1 and T3, but that both R3 and T2 significantly differed from R1 and T3 in mean penetration depth. While this suggests an effect of tip cross-sectional area on penetration performance, it is interesting to note that the poorest performing point in this group (T3) has the smallest TSCA, while the second worst performing point (R1) has the largest tip cross-sectional area. It is also worth noting that the worst (T3) and best (T2) points have identical mechanical advantages (Table 1). The *t*-test ($t = 2.8187$, $df = 18$, $p = 0.0114$) detected a significant difference between points R2 and T1, again suggesting an effect of tip cross-sectional area on point performance. Again, however, of these two points, the one with the largest tip cross-sectional area (R2) performed the best.

To test for the effects of tip cross-sectional perimeter on penetration depth, we conducted three t-tests (using a Bonferroni-adjusted $\alpha = 0.017$ to control the family-wide type I error rate [Rice, 1989], and using tests assuming equal or unequal variances, as appropriate, based on F-tests) between points or groups of point that differed in tip cross-sectional perimeter but that had the same tip cross-sectional area. As expected on the basis of the regression analysis, in every instance the sample with the smaller tip cross-sectional perimeter had a significantly greater mean penetration depth (Table 3).

Regression analysis detected a moderate yet significant relationship between mechanical advantage and penetration depth ($y = 1.3427x + 11.016$; $r^2 = 0.1816$) (Fig. 4). Alternative calculation of mechanical advantage for triangular points (considering them to have three rather than two cutting edges) resulted in a weaker relationship (but still significant) between mechanical advantage and penetration depth ($y = 0.96x + 10.642$; $r^2 = 0.1032$). Since mechanical advantage and tip cross-sectional perimeter are negatively correlated in our experimental points ($r = -0.4108$), we also examined the partial correlation between mechanical advantage and penetration depth holding tip cross-sectional perimeter constant. The resulting partial correlation coefficient ($pr_{TCSP} = 0.6804$) indicates a substantial effect of mechanical advantage independent of tip cross-sectional perimeter ($pr^2_{TCSP} = 0.4629$).

The edge sharpness index was moderately, yet significantly, inversely related to penetration depth in the experiment ($y = -0.015x + 14.763$; $r^2 = 0.3346$) (Fig. 4). Edge sharpness and tip cross-sectional perimeter are positively correlated in the experimental points ($r = 0.5468$), and the partial correlation coefficient (holding tip cross-sectional perimeter constant: $pr_{TCSP} = -0.5449$) suggests a moderate negative effect of edge sharpness on penetration independent of tip cross-sectional perimeter.

4. Discussion

The observed performance of points of varying shapes and sizes fired into ballistic gelatin supports the finding by Sisk and Shea (2009) and Sitton et al. (2020) that tip cross-sectional perimeter is a better predictor of point penetration than is tip cross-sectional area. This in turn suggests that skin surface drag may be the single-most important variable determining the penetration of prehistoric dart and arrow points. The lack of an observed relationship between tip cross-sectional area and penetration, along with the implication that form drag is a negligible source of resistance to point penetration, is surprising, especially given the apparent utility of this variable in differentiating armatures from different weapon delivery systems (see review in Lombard, 2021). It seems likely that form drag in semi-solid substances (like muscle or ballistic gelatin) is mitigated to some degree by the mechanical advantage and edge sharpness of the point, which serve to slice and displace material in advance of the arrival of the base or shoulder (with the greatest tip cross-sectional area). The utility of tip cross-sectional area as an indicator of weapon delivery system is no doubt a function of the positive covariance of tip cross-sectional perimeter and tip cross-sectional area ($r = 0.9133$ in 243 arrowheads and dart tips culled from the literature: Fig. 5 and Supplementary Material), and the positive relationship of both of these variables to overall point size. The

Table 3
Effect of tip cross-sectional perimeter on penetration depth, holding tip cross-sectional area constant.

Small TCSP	Mean PD[a]	Large TCSP	Mean PD[a]	t	df	p
R1 (9.00)	13.5 ± 0.47 (18)	R2 (11.18)	11.2 ± 0.21 (10)	17.981	25	<0.001
T2 (9.00)	14.1 ± 0.42 (11)	T1 (11.18)	10.9 ± 0.27 (10)	21.097	19	<0.001
T2 + R3 (9.00)	14.0 ± 0.31 (21)	T1 (11.18)	10.9 ± 0.27 (10)	24.845	29	<0.001

TCSP = tip cross-sectional perimeter (cm).
PD = penetration depth (cm).
[a] Mean ± SD (N) penetration depth.

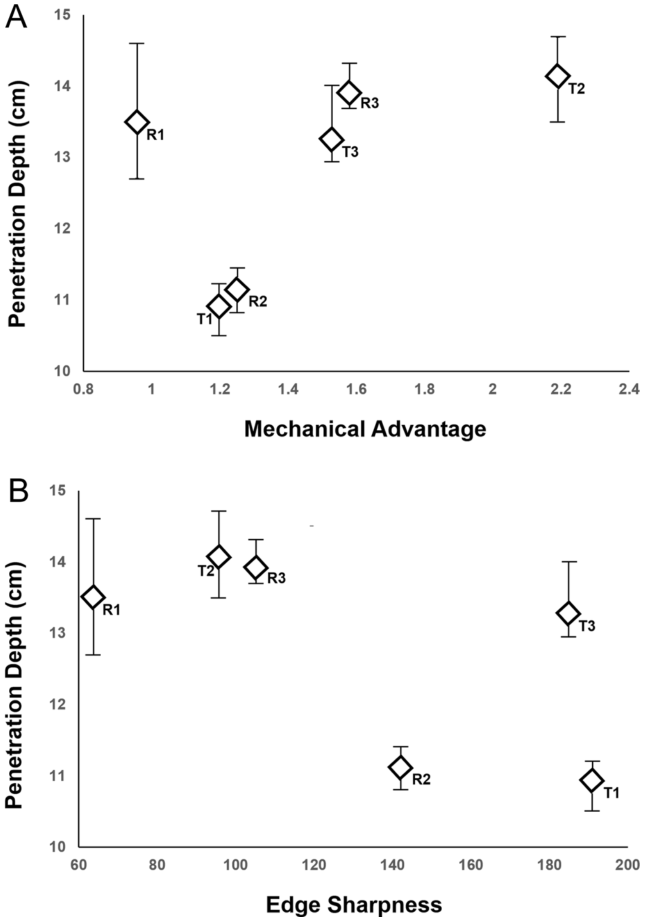

Fig. 4. Means (diamonds) and ranges (whiskers) of penetration depth (cm) of experimental point types, arranged by (A) mechanical advantage and (B) edge sharpness. Experimental point identifiers (see text) are provided adjacent to each set of values. See text for definitions of mechanical advantage and edge sharpness.

reduction in tip cross-sectional area along the thrusting spear – throwing spear – spear-thrower dart – bow-and-arrow continuum noted by Hughes (1998) reflects an overall point size reduction along this continuum that is likely related to several factors, including conservation of penetration performance at lower momentums, and tuning of armature mass to both the spine of the arrow or dart shaft and to the mechanics of the launching device (Hughes, 1998; Lepers and Rots, 2020). Accordingly, while tip cross-sectional perimeter may be the mechanically most-relevant measure of point size, tip cross-sectional area appears to be a reasonable proxy for point size (and thus useful for inferring weapon delivery system).

It is important to bear in mind, however, that penetration of a projectile is not the only variable affecting its lethality. The overall size of the wound channel, or total volume of tissue damage, is likely proportional to the amount of hemorrhaging induced in prey (Salem and Churchill, 2016). Since the total volume of tissue damage is equal to penetration depth * tip cross-sectional area, larger points that achieve moderate penetration depths may perform better than smaller points that penetrate more deeply. In this regard, point R1, which combines the largest tip cross-sectional area with the smallest tip cross-sectional perimeter among our experimental points, produced the greatest volume of tissue damage (Table 2).

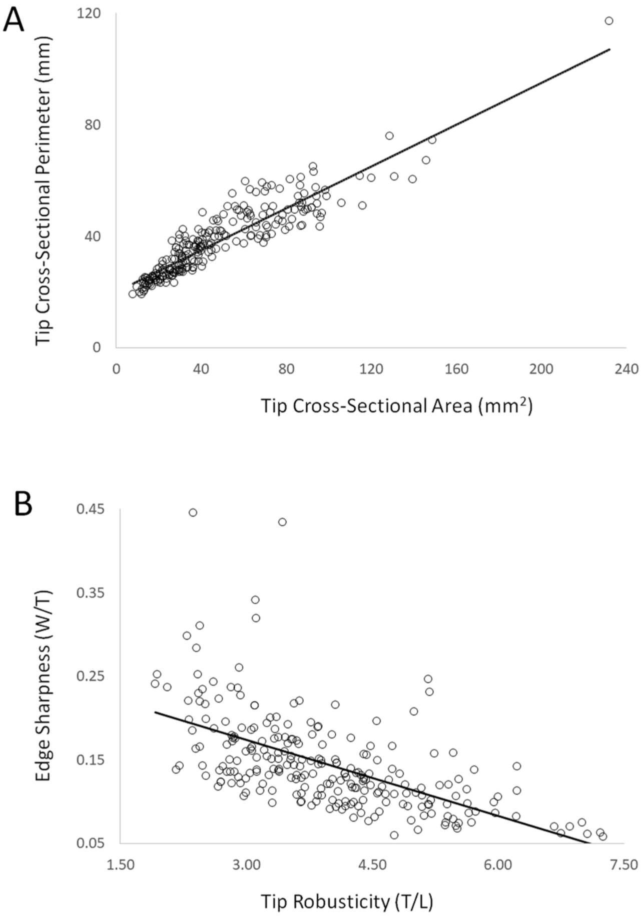

Fig. 5. (A) Tip cross-sectional perimeter (mm) versus tip cross-sectional area (mm^2) in a sample of lithic points. Regression line fit by ordinary least squares ($y = 0.3747x + 20.0290$; $r^2 = 0.8341$). (B) A measure of edge sharpness (point width/thickness) versus a measure of tip robusticity to snapping (point thickness/length) in a sample of lithic points. Regression line fit by ordinary least squares ($y = -0.0305x + 0.2656$; $r^2 = 0.346$). Note that the proxy edge sharpness measure used here differs from that used in the experiment. Data on dart points and arrowheads from the Americas ($n = 243$) were taken from Thomas (1978), Shott (1993, 1997), and Nami (2013), and are provided in the Supplementary Material.

The inverse relationship observed between edge sharpness and penetration depth is surprising. However, this finding is likely a function of the mechanical properties of ballistic gelatin, combined with the nature of the relationships between edge sharpness, tip cross-sectional perimeter, and mechanical advantage. Ballistic gelatin is brittle, with a fracture toughness two- to three-orders of magnitude lower than muscle tissue (see Czerner et al., 2013 vs. Taylor et al., 2012). Accordingly, the benefits of sharp edges that separate molecular bonds are likely to be much greater in muscle tissue (and skin and other organs) than they are in gelatin, where the mechanical advantage afforded by the point might produce fractures adjacent to its edges. It is also the case that edge sharpness is proportional to width/thickness, while mechanical advantage is proportional to length/width. And, for a given tip cross-sectional area, tip cross-sectional perimeter decreases as the ratio of thickness/width approaches one. Thus, increases in width that enhance edge sharpness will also increase tip cross-sectional perimeter and decrease mechanical advantage, and it is likely these constraints that produced the inverse relationship observed between edge sharpness and penetration depth. The importance of edge sharpness in actual hunting contexts is underscored by the high width/thickness ratios typically observed in bifacial points (3.96 ± 1.11 in 243 arrowheads and dart tips culled from the literature: data provided in Supplementary Material).

The discussion above highlights the multiple constraints that operate on projectile point design. For bifacial points, penetration performance can be enhanced (at any point size) by approximating a square cross-sectional shape at the base (producing the smallest tip cross-sectional perimeter for a given overall point size), but which in turn produces the least sharp edges (since edge sharpness is proportional to width/thickness). Tip cross-sectional perimeter and mechanical advantage are likely to covary inversely (which is good from a design perspective), since perimeter increases proportionally with width, while mechanical advantage is inversely proportional to width. However, mechanical advantage is proportional to point length, while a point's "robustness" against failure (i.e., snapping) is inversely proportional to length. Thus, functional demands for point durability necessitate proportional increases in point thickness as length increases (Buchanan and Hamilton, 2020; Cheshier and Kelly, 2006). Accordingly, mechanical advantage should vary as thickness/width (that is, inversely with edge sharpness): thick points which are robust to snapping sacrifice edge sharpness for durability (Fig. 5). These multiple constraints interact to prohibit optimization of point morphology for penetration performance, lethality, and durability: for example, narrowing a point would be expected to decrease tip cross-sectional perimeter and increase mechanical advantage (producing a positive effect on penetration depth), while simultaneously decreasing edge sharpness (negatively effecting penetration depth) and tip cross-sectional area (decreasing the total volume of tissue damage). In agreement with theoretical considerations of point design and function (Buchanan and Hamilton, 2020), the modal size and shape of lithic armatures in prehistory is likely to reflect the best compromise between penetration performance (and lethality) and durability, given the weapon system in use, local prey characteristics, and the multiple constraints that operate to prevent the simultaneous optimization of all the mechanically-relevant aspects of point morphology.

5. Conclusions

Experimental testing was conducted with 3D-printed arrowheads, which varied in their mechanical properties, fired into calibrated ballistic gelatin. The objective of this study was to evaluate the performance effects of four mechanically-relevant aspects of projectile point morphology (tip cross-sectional area, tip cross-sectional perimeter, mechanical advantage, and edge sharpness), as well as that of overall point cross-sectional shape (triangular versus rhomboidal). The experiment revealed a very strong (and statistically significant) effect of tip cross-sectional perimeter on penetration performance. Tip cross-sectional perimeter is directly proportional to skin surface drag; thus, these results suggest that this type of drag is a major factor in projectile point performance. Conversely, tip cross-sectional area was found to have a minimal (and statistically insignificant) effect on penetration depth in ballistic gelatin. Tip cross-sectional area is directly proportional to a second type of drag, known as form drag; thus, these results suggest that form drag is of minor importance to point penetration performance.

The experiment also revealed less important (but still statistically significant) positive effect of point mechanical advantage and negative effect of edge sharpness on penetration performance. The negative effect of edge sharpness is surprising, but is likely a function of (1) mechanical differences (namely, brittleness versus toughness) of ballistic gelatin versus animal tissues that may mask the importance of edge sharpness in real-life hunting contexts, and (2) design constraints that result in positive covariance between edge sharpness and tip cross-sectional perimeter (such that, for a given overall point size, efforts to decrease tip cross-sectional perimeter will also decrease edge sharpness). This latter factor is one of multiple constraints that limit the ability of flint knappers to optimize all of the mechanically-important variables that are important to projectile point function.

Contributions: JHG and SEC contributed equally to the paper.

CRediT authorship contribution statement

Jackson H. Grady: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Steven E. Churchill:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

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