Journal of Archaeological Science: Reports 42 (2022) 103399

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Experimental assessment of lanceolate projectile point and haft robustness

Briggs Buchanan [a,*], Robert S. Walker [b], Marcus J. Hamilton [c], Brett Story [d], Michelle Bebber [e], Dan Wilcox [e], Metin I. Eren [e,f]

[a] Department of Anthropology, University of Tulsa, Tulsa, OK, USA
[b] Department of Anthropology, University of Missouri, Columbia, MO, USA
[c] Department of Anthropology, University of Texas at San Antonio, San Antonio, TX, USA
[d] Department of Civil and Environmental Engineering, Lyle School of Engineering, Southern Methodist University, Dallas, TX, USA
[e] Department of Anthropology, Kent State University, Kent, OH, USA
[f] Department of Archaeology, Cleveland Museum of Natural History, Cleveland, OH, USA

ARTICLE INFO

Keywords:
Experimental archaeology
Stone weapon tips
Hafts
Robustness
Bayesian analysis

ABSTRACT

Stone lanceolate projectile points are characterized as having a lance shape with a tip tapering to an apex and are found in the archaeological record at different times and places across the world. In North America, lanceolate points are an important component of the Paleoindian period. One of the main factors in the design of lanceolate points is robusticity, which refers to how much of a point breaks as a result of failure of the stone upon impact. In this paper we investigate the factors that influence the robustness of lanceolate projectile points. To do this, we present results of a controlled ballistic experiment using 412 projectile points of 14 different lanceolate forms to investigate differences in point robustness. We hafted these points to darts and fired them into an oak board to induce impact failure. We then analyzed the resulting point breakage and haft damage. To assess the influence of point characteristics on point breakage we constructed a Bayesian zero-inflated negative binomial regression model. Results show short, wide, and thick blade forms were more robust than long, narrow, and thin blades. Using a separate Bayesian binomial model, we also found that haft damage occurred more often with the more robust points. Therefore, we suggest that a trade-off between point and haft robustness was likely an important consideration for prehistoric flintknappers when designing their weapons.

1. Introduction

Damage to cryptocrystalline stone weapon tips during use is undoubtedly one of the important factors that prehistoric hunters considered when designing weaponry (Cheshier and Kelly, 2006; Knecht, 1997; Loendorf et al., 2018; Odell and Cowan, 1986). Like other performance characteristics–such as penetration, aerodynamics, sharpness, and multifunctionality–point robustness (the ability to withstand breakage) was an attribute either consciously or unconsciously manipulated by prehistoric peoples in specific settings (Buchanan and Hamilton, 2020; Eren et al., 2021; Iovita et al., 2014; Pargeter 2007; Wilkins et al., 2012). In some contexts, stone weapon tips may have been designed to resist breakage (Thomas et al., 2017), in other contexts foragers may have created points to increase the chances of fracturing and therefore causing more damage (Bebber et al., 2017; Engelbrecht, 2015; Mika et al., 2020). Here, we focus on the former, situations where the goal was to produce robust points capable of withstanding breakage. Point robustness is closely linked to the concept of durability, or the capacity of a stone point to endure catastrophic damage from impact (Cheshier and Kelly, 2006; Maguire et al., 2022), however, robustness, as used in this study, specifically refers to the amount of breakage or loss of material after the point or haft fails upon impact. Thus, a robust point, in our usage, refers to a point that sustains little breakage after impact failure and has the potential to be reworked and used again, whereas durability refers to the number of times a point can be used before significant damage prohibits further use.

Several experimental studies focused on stone weapon tip durability have shown that the maximum number of shots that a stone weapon tip tolerates is 10 or less (Cheshier and Kelly, 2006; Odell and Cowan, 1986; Sisk and Shea, 2009; Titmus and Woods, 1986). These studies were actualistic experiments on the realistic end of the experimental continuum (that is, experiments with more external validity [actualistic or realistic] rather than internal validity [more controlled], cf. Eren et al., 2016), as they used animal carcasses as targets (real or simulated by

* Corresponding author.
E-mail address: briggs-buchanan@utulsa.edu (B. Buchanan).

https://doi.org/10.1016/j.jasrep.2022.103399
Received 6 December 2021; Received in revised form 11 February 2022; Accepted 22 February 2022

bringing together animal parts). In these experiments the probability of damage primarily relates to the chance of the stone point hitting bone, thus durability, as measured in these studies, is contingent on the mapping between carcass and weapon tip configurations (i.e., distance of point to carcass, angle and velocity of shot, location of bone relative to stone tip trajectory, etc.). The limitations of these actualistic experiments is derived from their realism, and thus, depending on the investigated question, generalizing inferences from these actualistic studies is difficult, though inferences drawn through comparison might lead to limited generalizations. For example, points were more durable (number of shots to catastrophic damage) when shot into larger carcasses (Cheshier and Kelly, 2006) relative to points shot into smaller carcasses (Odell and Cowan, 1986), suggesting carcass size and thus probability of impacting a bone is a relevant factor in durability. Within this domain, the work of Odell and Cowan (1986) and Cheshier and Kelly (2006) are important early exploratory studies of projectile point durability that engaged with issues of experimental control versus realism, as well as the use of morphometrics to carry out inferential statistical testing at a time when authoritative approaches based on knapper or hunter experience were still dominant (e.g., Thomas, 1986; Frison, 2004). In particular, Cheshier and Kelly (2006) proposed that a stone tip's thickness-to-length ratio (T:L) influenced impact durability. Their inference was drawn from shooting 50 triangular side-notched points with varying T:L into deer carcasses and suggested that points with T:L greater than 0.121 (an arbitrary cutoff) were "slightly, but significantly" more resistant to breakage than were points with a T:L less than this value.

More recent theoretical modeling and empirical investigations of lanceolate projectile points demonstrates that optimal robustness or durability was an apparent goal for most North American Paleoindian lanceolate point designs (Buchanan and Hamilton, 2020). Lanceolate projectile points, which are generally characterized as having a lance shape with a tip tapering to an apex, are an important component of the North American Paleoindian archaeological record, as well as having been made and used in other regions and time periods (e.g., Benedict and Olson, 1973; Cooke, 1998; Hoffecker, 2001; Jennings et al., 2015; King and Slobodin, 1996; Scott et al., 1986; Wadley, 2007). Buchanan and Hamilton's (2020) model was based on fundamental physical design properties of lanceolate points to withstand a critical load and resist buckling or breakage. This usage aligns closely with the concept of durability as implemented in the experiments carried out by Odell and Cowan (1986) and Cheshier and Kelly (2006). Buchanan and Hamilton (2020) showed that lanceolate point durability is determined by the slenderness ratio (the ratio of point length to the effective radius), with low ratios producing greater durability. Importantly, they also found a design trade-off between durable points manufactured to withstand buckling versus the ability of slender points to penetrate more deeply (Buchanan and Hamilton, 2020). Empirical evidence from the scaling relationships of Paleoindian lanceolate point dimensions shows that many types were designed to balance durability with penetration capability. This is also the relationship that Cheshier and Kelly (2006) found empirically in their experimental firings of different forms of triangular side-notched points: points with a greater T:L were more durable than points with a lower T:L.

In this study, we build on the findings from the theoretical modeling, experimental, and empirical investigations of point durability cited above by examining the after-effects of impact damage on lanceolate stone points and hafts. We assume that keeping the stone point and haft as intact as possible was desirable because both were costly to make. The conchoidally-fracturing stone (chert, obsidian, etc.) used to make lanceolate points is heterogeneously distributed across the landscape and requires time and effort to obtain, as does the skill to transform the stone into points. Similarly, the organic materials used to make the haft and the skill needed to construct the haft took time and effort to obtain. Thus, it is assumed that keeping the point and haft intact was desirable and keeping more of the point and haft intact increased the chances of being able to rework or repair the damaged parts and extend the use life of the weapon. To investigate robustness in stone lanceolate points and hafts, we designed our experiment to induce impact damage by firing stone lanceolate points at an oak board target. We then examined the resulting point breakage and haft damage. Our sample of replica points includes 14 different lanceolate forms which we used nearly 30 specimens of each type in our experimental firings. We analyzed the results using a Bayesian model designed to capture how various point characteristics influence point and haft damage after impact.

2. Materials and methods

2.1. Production of lanceolate projectile points and hafts for robustness experimentation

We had 14 different lanceolate projectile forms made for our experiment. Seven of the lanceolate forms we used were modeled from actual Clovis (North American early Paleoindian) artifacts that represent the extremes of the known plan-view shape variation of Clovis (see Buchanan et al., 2014) (Fig. 1). The procedures used to define the shape variation and selection of representative Clovis specimens are detailed in Eren et al. (2020). The other seven lanceolate forms are based on the plan view shape outlines of the seven Clovis forms but standardized in length (to 7.9 cm), which reduces or extends the length of the seven initial forms accordingly Fig. 1. Therefore, the 14 point forms in our sample represent a wide range of possible lanceolate forms found across the world.

Craig Ratzet of Neolithics Flintknapping Supply House (www.neolithics.com) used the plan view design specifications of the 14 lanceolate point forms to produce ground stone specimens from Texas Fredericksburg chert (Eren et al., 2020). Producing ground stone point replicas, rather than flaking points by flintknapping, increased the consistency with which we could produce multiple specimens of each of the forms in a timely and cost-effective manner. While the use of ground points instead of flaked points reduces the external validity of the experiment, we note that a recent study by Lowe et al. (2019) comparing flaked and ground projectile points found no statistical difference in durability between the two suggesting that ground replicas are a reasonable alternative for flaked points.

Bob Berg of Thunderbird Atlatl (www.thunderbird.com) hafted each of the stone points to wood darts. The hafting procedure was consistent across all points in our sample. Berg attached the stone points to ½ inch ash dowels, which he milled individually for a close fit between the point and the wood. After which, he wrapped hemp fiber lashings around the juncture of the stone and wood and sealed them with Kodak gelatin-based glue dissolved in warm water. More details on the hafting can be found in Eren et al. (2020).

Our aim was to have 30 ground replica points for each of the 14 lanceolate forms for a total of 420 points. However, a production problem with lanceolate form #3 gave us only 23 specimens, and the accidental breakage of a specimen from the lanceolate form #8 sample, gave us a total of 412 points for the durability experiments (Fig. 2). Raw data and descriptive statistics for each sample of the 14 ground lanceolate point types are available in the Supplementary Materials.

3. Experimental firing procedures

We fired each of the specimens from the 14 replica lanceolate point samples with a 29 lbs. PSE compound bow mounted on a Spot-Hogg Hooter Shooter in the Kent State University Experimental Archaeology Laboratory (see Eren et al., 2022). We used a sheet of oak (2.54 cm thick) as the target, which was set in a vertical position two meters from the compound bow. We selected wood as our target for several reasons: wood is common and inexpensive and makes replication easier, wood is a material that could have accidently been hit by prehistoric hunters (unlike clay blocks or porcelain tiles), and the use of wood enhances the

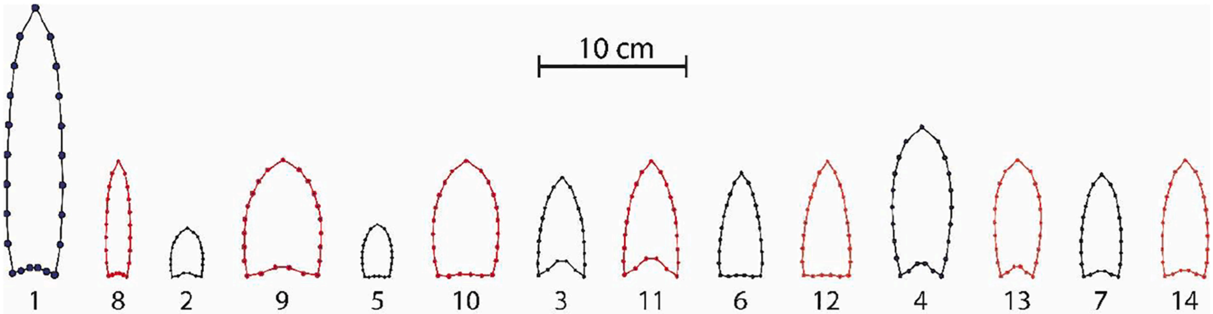

Fig. 1. Outlines of the 14 different lanceolate forms. The circles show the location of the landmarks used to digitize the archaeological specimens. The black outlines are the seven Clovis forms and the red outlines are the same forms adjusted to a standard length (7.9 cm).

Fig. 2. The 412 hafted stone points comprising 14 different lanceolate forms.

probability of damage, the focus of our study.

We followed the experimental protocol of Eren et al. (2022) and fired each hafted projectile point (n = 412) at the oak target until either the stone point or haft was damaged. We shot the darts from a standardized bow draw length of 56 cm. Keeping the bow length standard rather than the velocity has the effect of simulating the actions of a single individual, as it is unlikely that a person would increase or decrease their bow draw ability based on the weight of the projectile tip. We recorded velocity using a Gamma Master Model Shooting Chronograph throughout the experiment. Although reading errors were common, we note that the velocities are within the range of human atlatl throwing velocities (Whittaker et al., 2017; see Supplementary Materials). Each projectile was repeatedly fired until damage to the point or haft was observed, after which the damage was recorded, and the specimen was not fired again. Damaged projectiles were photographed. Point breakage was calculated as the length lost. Subsequently, we calculated the percent of the point remaining by dividing the original point length by the length of the point after receiving damage and this variable, 'percent broken', was used in our statistical analyses. Haft damage in the form of split lashings, split shafts, and points loose from their hafts was recorded as present or absent.

4. Statistical model of after impact point and haft damage

We constructed a Bayesian zero-inflated negative binomial regression model of lanceolate point and haft damage. The zero-inflated negative binomial model works with count variables that have an excessive occurrence of zeroes and is commonly used for overdispersed count outcome variables (Ghosh et al., 2006; see Gelman et al., 2013 for an overview of Bayesian data analysis). Our sample distribution of percent broken point lengths exhibits these properties, an excess of zeroes and a long tail (the points recorded as zero percent broken had haft damage that precluded further firing; Fig. 3). Zero-inflated models assume that the excess of zeroes is generated by a separate process from the count values and that the excess zeroes can be modeled independently. We used the zero-inflated negative binomial model to conduct a simultaneous analysis of the probability of breakage, either of the point or haft, after sequential firings with an analysis of the percent broken after any type of damage is incurred. For the predictors in our model we focused on two continuous variables, point maximum length and

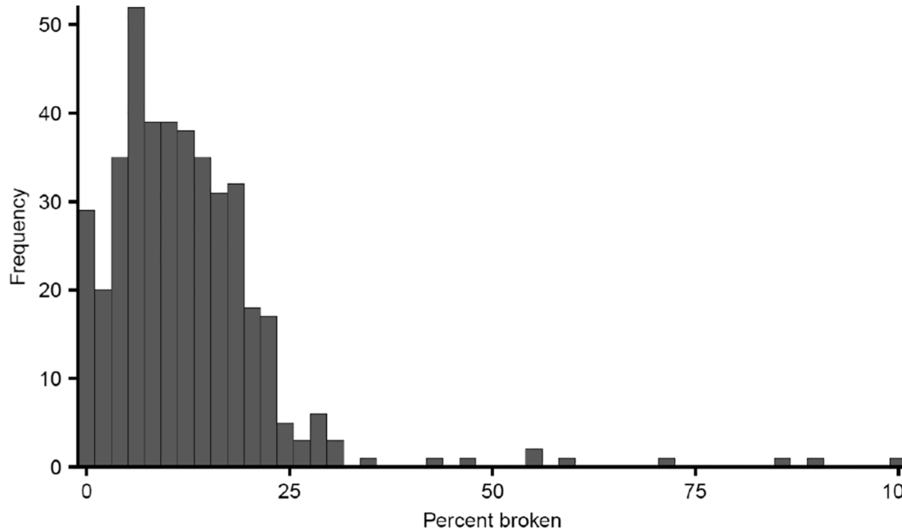

Fig. 3. Histogram of the frequency of lanceolate points with the percent broken after damage was incurred on the point or haft. Note the high frequency of zero percent broken and the long right tail of the distribution.

thickness, that have found to be empirically (Cheshier and Kelly, 2006; Eren et al., 2022; Maguire et al., 2022) and theoretically (Buchanan and Hamilton, 2020) important components of durability. We also include the 14 lanceolate point types as a categorical predictor that incorporates outline shape into our model. We fit the zero-inflated negative binomial regression model in R 3.6.1 (R Core Team) with the *brms* package. A hierarchical modeling approach was selected to adjust for the ca. 30 repeat sample experimental firings of each point form. Weak prior probability distributions (priors) were assigned to all parameter values. Sampling was carried out using the No-U-Turn Sampler (NUTS) developed by Hoffman and Gelman (2014) to improve upon the Hamiltonian Monte Carlo-Markov Chain procedure. Final models were run with 2 chains for 10,000 iterations with a 'warm-up' of 5000 iterations. The warm-up phase is used to determine the step size by maximizing the acceptance rate of proposals. For all parameters, r-hat values (a model diagnostic with expected value equal to 1) were exactly 1.00 and hence ensure model convergence. Chains were also inspected visually for sufficient mixing to ensure that model results were appropriate. We used posterior distributions to make inferences about the strength of the effects in the model.

Next, we independently analyzed haft damage, including any observation of a split shaft, split lashings, or a point coming loose from the haft, using a Bayesian binomial model. For the Bayesian binomial model we used a logit link function and included haft width, haft length, and haft thickness as predictors of haft damage. As with the model above, we also include the 14 lanceolate point types as a categorical predictor that incorporates outline shape into our model. We fit the binomial regression model in R 3.6.1 (R Core Team) with the *brms* package using the same priors and procedures described above.

5. Results

By design, firing our hafted replica points into oak resulted in most darts incurring damage (either in the point or haft) on the first shot. Of the 14 lanceolate point forms that we fired, nine of the samples (#'s 2, 3, 5, 6, 7, 8, 12, 13, and 14) were shot only once each before suffering damage. Samples 1, 4, 9, 10, and 11 were shot more than once and hence were more durable. Of these, sample 9 was shot the most before breaking (see Supplemental Materials). Although these results are not directly comparable to the actualistic experiments of Odell and Cowan (1986) and Cheshier and Kelly (2006), they do meet our expectation that this experiment induces damage.

6. Bayesian model of lanceolate point and haft damage

Our Bayesian zero-inflated negative binomial model had an overall $r^2 = 0.28$. The zero-inflation part of the model, predicting if a point or haft would break or not, showed that the intercept, length, and thickness have no effect, but there is a small effect of point type (Table 1). Only point 9 shows a significant intercept, and it also has the highest odds ratio, indicating that this point was most likely to remain intact (Table 2). Again, this result also is not unexpected given that we designed this experiment to produce damage and essentially override the durability of each of the lanceolate forms.

The second part of this model, predicting the percent broken, indicates more of an overall effect and the intercept, thickness, and length are significant (Table 1). This indicates that thin and short lanceolate points are more likely to have more damage than thicker, longer points (Fig. 4). The estimates for after point or haft breakage are given in Table 3 (the posterior distribution for this part of the model are reverse coded as per convention). The posterior distributions show that five of the point types have a significant effect, point forms 9, 10, and 4 have the lowest percent broken and point forms 6 and 8 have the highest percent broken (Fig. 5). Point forms 9, 10, and 4 have wide blades and tips, whereas point forms 6 and 8 have narrow blades and tips.

For haft damage, we carried out a Bayesian binomial model of the incidences of split shafts, split lashings, or a point coming loose from the haft using haft dimensions (length, width, and thickness) as predictors. For the overall model the $r^2 = 0.34$ (Table 4). The model indicates that

Table 1
Results of Bayesian zero-inflated negative binomial model of percent broken predicted by point length, thickness, and type (zi = zero-inflated).

Group-level Effects (14 point types)				
	Estimate	Est. Error	Q2.5	Q97.5
sd (zi-intercept)	1.28*	0.61	0.35	2.75
sd (intercept)	0.38*	0.10	0.24	0.63
Population-level Effects				
	Estimate	Est. Error	Q2.5	Q97.5
zi-intercept	−3.30	2.38	−7.71	1.67
zi-length	−0.02	0.02	−0.07	0.02
zi-thickness	0.25	0.35	−0.45	0.92
Intercept	3.95*	0.39	3.17	4.69
Length	−0.01*	0.00	−0.01	0.00
Thickness	−0.12*	0.05	−0.22	−0.03

*Significant effect.

Table 2
Intercepts for point types for the zero-inflated part of the Bayesian negative binomial model of percent broken predicted by point length, thickness, and type.

Point type	Estimate	Est. Error	Odds ratio	Q2.5	Q97.5
1	−0.26	1.38	0.771	−3.45	2.33
2	−0.14	0.95	0.869	−2.11	1.77
3	−0.16	0.97	0.852	−2.34	1.53
4	0.22	1.09	1.246	−2.09	2.25
5	0.53	0.92	1.699	−1.26	2.43
6	−0.94	1.20	0.391	−3.85	0.84
7	−1.03	1.17	0.357	−3.88	0.71
8	−0.06	0.89	0.942	−1.96	1.62
9	1.76*	0.90	5.812	0.14	3.67
10	0.79	0.81	2.203	−0.67	2.50
11	−0.28	0.98	0.756	−2.56	1.41
12	−0.96	1.16	0.383	−3.74	0.75
13	−0.28	0.96	0.756	−2.39	1.44
14	−1.10	1.13	0.333	−3.78	0.64

*Significant effect.

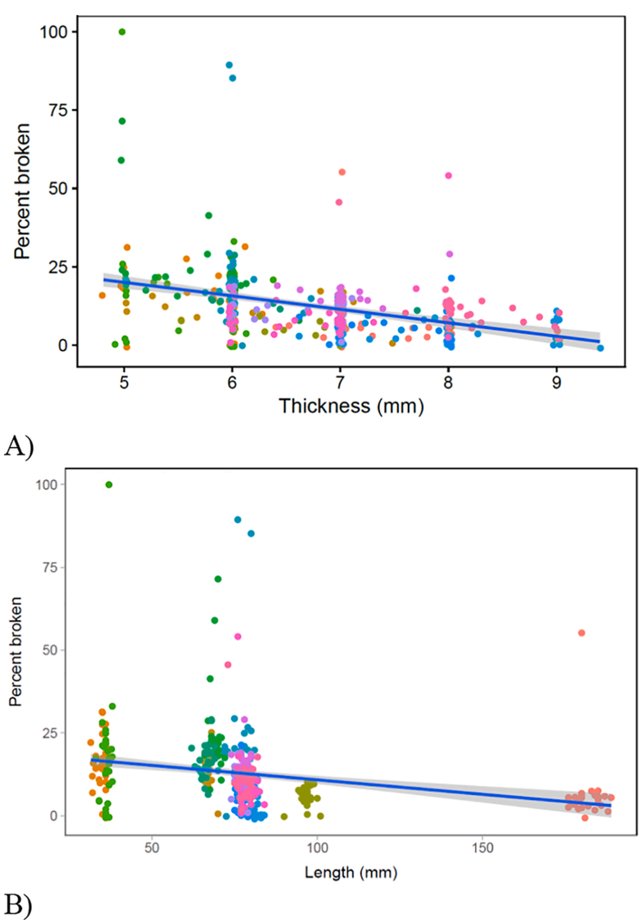

Fig. 4. Point A) thickness and B) length in millimeters by percent broken (color = point form, see Fig. 5 to match the color to the different point forms).

point form and haft length have an effect, with point configurations with shorter hafts having less damage. The negative credible intervals for this model indicate less damage, indicating that point forms 1 and 6 had significantly less haft damage and point form 13 had more (Table 5; Fig. 6).

7. Discussion

Models of stone point robustness demonstrate that the durability of a point is a function of the slenderness ratio (Buchanan and Hamilton, 2020). Points that are too thin relative to their length will buckle and break when under critical load. Our experiment in this paper created a situation where most lanceolate forms experienced breakage after being fired close range into an oak board. Our goal was to examine the aftereffects of this impact failure and determine if the original shape and size of the lanceolate resulted in differential point and haft breakage. In

Table 3
Intercepts for point types for the after-damage Bayesian negative binomial model of percent broken predicted by point length, thickness, and type.

Point type	Estimate	Est. Error	Q2.5	Q97.5
1	0.23	0.35	−0.43	0.96
2	−0.10	0.19	−0.49	0.27
3	−0.02	0.15	−0.32	0.28
4	−0.40*	0.16	−0.71	−0.09
5	0.04	0.19	−0.34	0.41
6	0.45*	0.14	0.18	0.75
7	0.14	0.14	−0.14	0.42
8	0.52*	0.14	0.25	0.80
9	−0.57*	0.18	−0.94	−0.23
10	−0.42*	0.15	−0.74	−0.12
11	−0.07	0.14	−0.35	0.20
12	0.22	0.14	−0.06	0.49
13	−0.17	0.14	−0.46	0.11
14	0.11	0.15	−0.19	0.41

*Significant effect.

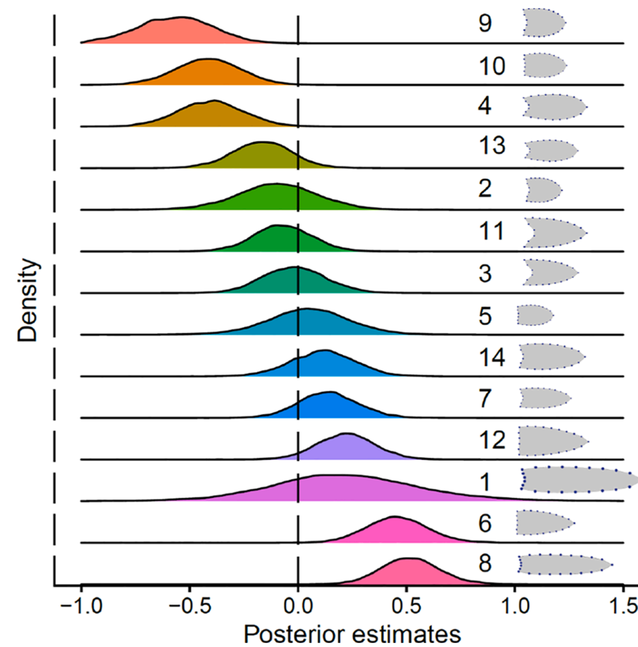

Fig. 5. Posterior distributions from the Bayesian zero-inflated negative binomial model for percent broken.

Table 4
Results of Bayesian binomial model of haft damage.

Group-level Effects (14 point types)				
	Estimate	**Est. Error**	**Q2.5**	**Q97.5**
sd (intercept)	2.46*	0.73	1.38	4.19
Population-level Effects				
	Estimate	**Est. Error**	**Q2.5**	**Q97.5**
Intercept	10.11*	3.53	3.44	17.36
Haft width	−0.09	0.07	−0.24	0.04
Haft thickness	−0.18	0.19	−0.55	0.20
Haft length	−0.09*	0.03	−0.15	−0.04

*Significant effect.

Table 5
Intercepts for point types for the haft damage Bayesian binomial model.

Point type	Estimate	Est. Error	Odds ratio	Q2.5	Q97.5
1	−4.60*	1.56	0.010	−8.34	−2.12
2	2.43	1.82	11.359	−0.48	6.77
3	−0.15	1.05	0.861	−2.14	1.94
4	0.64	0.85	1.896	−1.01	2.35
5	2.12	1.89	8.331	−0.92	6.52
6	−2.01*	0.84	0.134	−3.71	−0.41
7	−0.51	0.90	0.600	−2.31	1.27
8	−1.33	1.25	0.264	−3.86	1.07
9	2.51	1.53	12.305	−0.42	5.71
10	0.32	1.14	1.377	−1.88	2.63
11	0.14	0.83	1.150	−1.50	1.77
12	−0.90	0.80	0.407	−2.49	0.64
13	3.53*	1.71	34.124	0.86	7.51
14	−0.48	0.84	0.619	−2.16	1.16

*Significant effect.

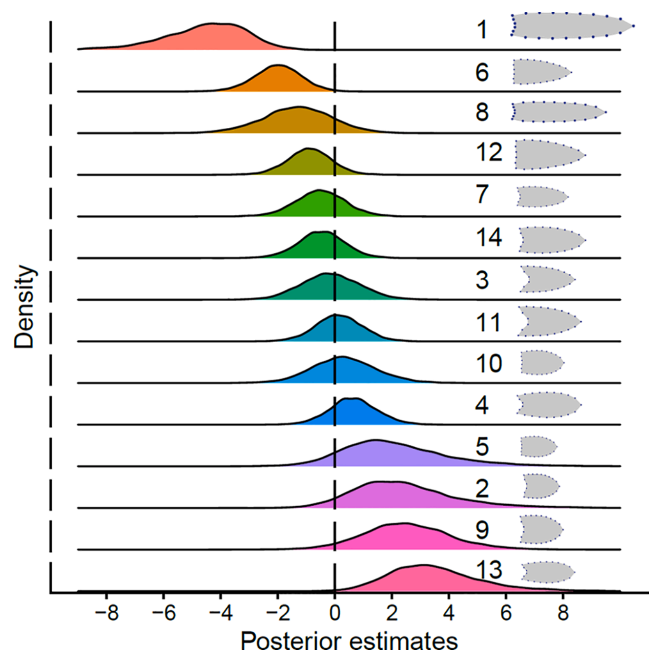

Fig. 6. Posterior distributions from the Bayesian binomial model for haft damage.

other words, within the variety of lanceolate point forms observed in the late Pleistocene North American archaeological record, which forms are the most robust?

Our results clearly showed that lanceolate stone points of varying form suffer differential damage, an important initial observation to establish as a baseline as this is the first controlled experiment to investigate lanceolate robustness. This initial finding suggests that prehistoric knappers were likely aware of the differential damage and may have made choices regarding lanceolate stone point design with regard to this design attribute.

Furthermore, the Bayesian model of the aftereffects of impact damage indicated that five of the point forms had a significant effect, with point forms 9, 10, and 4 having the lowest percent broken and point forms 6 and 8 having the highest percent broken. Contrasting these two sets of lanceolates shows that the best surviving forms (point forms 9, 10, and 4) have wide blades and tips, whereas the most damaged lanceolates (point forms 6 and 8) have narrow blades and tips. We also note that overall the results demonstrate an overlapping pattern of the posterior distributions (regardless of the significance) indicating a gradient of greater to lesser robustness in the 14 forms. However, given that the largest effects are associated with only five points of the 14, it is likely that prehistoric knappers did not differentiate among the entire spectrum of lanceolate forms represented in our experiment, but perhaps when considering robustness (whether it be preserve as much of a point as possible after impact, or conversely to have a point obliterate on impact) knappers conceivably differentiated among the short, wide blade forms and the narrow blade forms while adjusting the slenderness ratio accordingly.

It is unknown how Paleoindians hafted their lanceolate points to darts or how lanceolate hafting in other parts of the world may differ from the Paleoindian hafting arrangements. Thus, our hafting assembly—points affixed to milled ash dowels with hemp fiber lashings and glue—may have particular effects on the overall durability of the weapon system (i.e., the point, haft, and dart) that does not map on directly to particular prehistoric cases (Wilson et al., 2021). Nevertheless, in our study, all aspects of the weapon system are standardized across the 14 different lanceolate forms, allowing us to draw inferences concerning the relative durability of the haft when used with stone lanceolate points. In other words, while the prehistoric form of hafting remains unknown, the internal validity of the experiment is high (Eren et al., 2016). Therefore, given our hafting arrangement, our results demonstrated that hafts associated with point types 1 and 6 incurred little to no damage, whereas point type 13 yielded the most haft damage. Thus, it appears that hafts with points that incurred significant damage preserve the hafts better than points with less damage. This trade-off is visualized in Fig. 7, although the fit of this model is not very high, it is reasonable to speculate that point damage can preserve the haft and vice versa, and that several point forms (3, 7, 11, 12, and 14) balance these two concerns. It appears that basal shape plays little role in the haft-point damage trade-off.

Overall, statistical modeling of our experimental results was able to identify lanceolate forms that were more robust, that is retained more of the point relative to other forms after impact. Thus, given that some flexibility in the choice of lanceolate outline shape was afforded to prehistoric knappers, some knappers may have designed their points to be more robust. However, robustness does not come without a cost and more robust points unavoidably reduce penetration capability. Penetration capability is a critical factor in the effectiveness of a weapon to cause death of a prey animal. Moreover, the more robust points may also

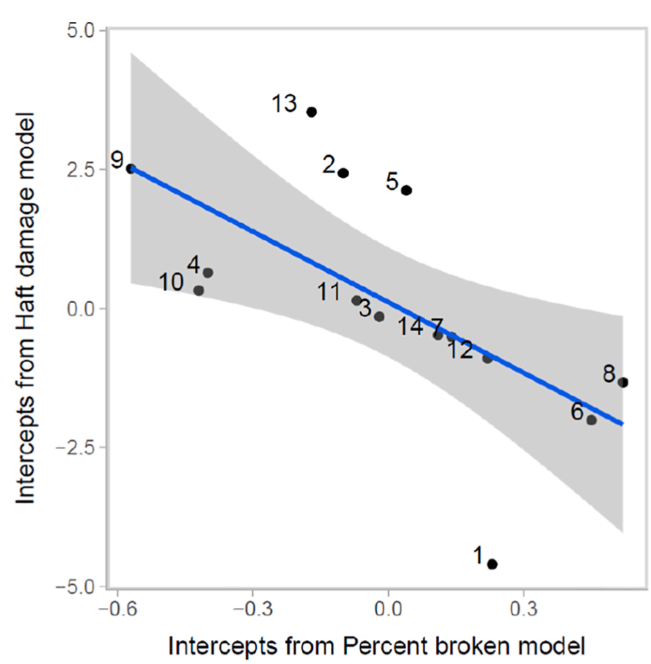

Fig. 7. Plot of intercepts from the second part of the Bayesian zero-inflated negative binomial model, the ‘percent broken’ model, and the Bayesian binomial model of haft damage showing the trade-off between the two.

have a cost in terms of haft damage. Thus, we can speculate that the foragers using stone lanceolate forms in contexts where suitable stone resources were scarce may have emphasized robustness in their point design (making forms similar to 9, 10, and, 4; see Fig. 1). On the other hand, in other contexts where good toolstone is easily available prehistoric knappers may have opted to make lanceolate points that stressed penetration capability and thus reduced robustness.

The experimental results we presented here emphasized control or internal validity over realism (Eren et al., 2016; Lin et al., 2018; Lin and Premo 2021). Our goal was to rigorously examine the robustness of points and generalize our findings if not to lanceolate stone point forms found in any spatial or temporal archaeological context, but also to other stone point forms. Obviously, to do the latter will require the usual call for further additional experiments, but hopefully future work can build upon our results. Unfortunately, it is too often the case that – depending on the question or variable of interest – the realized and hidden complexities of more realistic archaeological experiments limit our ability to build on previous experimental work and infer general patterns that are useful for archaeological inference. In the domain of experiments discussed in this paper, limitations to making inferences and extrapolating findings are usually a consequence of the chance aspect inherent in the design of experiments. Measuring durability in these previous cases has come down to the probability of hitting bone or not when firing points into real or simulated animal carcasses, and not to the inherent robustness of the points. While our experiment was relatively limited in terms of its external validity, we hope that more work in this direction, albeit via small increments, can be used to shed more light onto the past.

CRediT authorship contribution statement

Briggs Buchanan: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Robert S. Walker:** Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Marcus J. Hamilton:** Formal analysis, Writing – original draft, Writing – review & editing. **Brett Story:** Conceptualization, Writing – review & editing, Funding acquisition. **Michelle Bebber:** Investigation, Resources. **Dan Wilcox:** Investigation, Resources. **Metin I. Eren:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Funding acquisition.

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.

Acknowledgement

This research was funded by the National Science Foundation (Award IDs: 1649395, 1649406, 1649409).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2022.103399.

References

Bebber, M.R., Lycett, S.J., Eren, M.I., 2017. Developing a stable point: evaluating the temporal and geographic consistency of Late Prehistoric unnotched triangular point functional design in Midwestern North America. J. Anthropol. Archaeol. 47, 72–82.
Benedict, J.B., Olson, B.L., 1973. Origin of the McKean complex: evidence from timberline. Plains Anthropologist 18 (62), 323–327.
Buchanan, B., Hamilton, M.J., 2020. Scaling laws of paleoindian projectile point design. J. Archaeol. Method Theory 28 (2), 580–602.
Buchanan, B., O'Brien, M.J., Collard, M., 2014. Continent-wide or region-specific? a geometric morphometrics-based assessment of variation in Clovis point shape. Archaeol. Anthropol. Sci. 6 (2), 145–162.
Cheshier, J., Kelly, R.L., 2006. Projectile point shape and durability: the effect of thickness:length. Am. Antiq. 71 (2), 353–363.
Cooke, R., 1998. Human settlement of central America and northernmost South America (14,000–8000 BP). Quat. Int. 49-50, 177–190.
Engelbrecht, W., 2015. Interpreting broken arrow points. Am. Antiq. 80 (4), 760–766.
Eren, M.I., Lycett, S.J., Patten, R.J., Buchanan, B., Pargeter, J., O'Brien, M.J., 2016. Test, model, and method validation: the role of experimental stone artifact replication in hypothesis-driven archaeology. Ethnoarchaeology 8 (2), 103–136.
Eren, M.I., Story, B., Perrone, A., Bebber, M., Hamilton, M., Walker, R., Buchanan, B., 2020. North American Clovis point form and performance: an experimental assessment of penetration depth. Lithic Technol. 45 (4), 263–282.
Eren, M.I., Bebber, M.R., Wilcox, D., Story, B., Buchanan, B., 2022. North American Clovis point form and performance II: an experimental assessment of point, haft, and shaft durability. Lithic Technol. 47 (1), 38–51. https://doi.org/10.1080/01977261.2021.1926724.
Frison, G.C., 2004. Survival by Hunting. University of California Press.
Gelman, A., Carlin, J.B., Stern, H.S., Dunson, D.B., Vehtari, A., Rubin, D.B., 2013. Bayesian Data Analysis, third ed. Chapman and Hall, New York.
Ghosh, S.K., Mukhopadhyay, P., Lu, J.-C., 2006. Bayesian analysis of zero-inflated regression models. J. Statistical Plann. Inference 136 (4), 1360–1375.
Hoffecker, J.F., 2001. Late Pleistocene and early Holocene sites in the Nenana River valley, central Alaska. Arctic Anthropol. 38, 139–153.
Hoffman, M.D., Gelman, A., 2014. The No-U-Turn sampler: adaptively setting path lengths in Hamiltonian Monte Carlo. J. Mach. Learn. Res. 15 (1), 1593–1623.
Iovita, R., Schönekeß, H., Gaudzinski-Windheuser, S., Jäger, F., 2014. Projectile impact fractures and launching mechanisms: results of a controlled ballistic experiment using replica Levallois points. J. Archaeol. Sci. 48, 73–83.
Jennings, T.A., Smallwood, A.M., Waters, M.R., 2015. Exploring late Paleoindian and early Archaic unfluted lanceolate point classification in the Southern Plains. North Am. Archaeol. 36 (4), 243–265.
King, M.L., Slobodin, S.B., 1996. A fluted point from the Uptar site, northeastern Siberia. Science 273 (5275), 634–636.
Knecht, H., 1997. The history and development of projectile technology research. In: Knecht, H. (Ed.), Projectile Technology. Springer, Boston, pp. 3–35.
Lin, S.C., Premo, L.S., 2021. Forager mobility and lithic discard probability similarly affect the distance of raw material discard from source. Am. Antiq. 86 (4), 845–863.
Lin, S.C., Rezek, Z., Dibble, H.L., 2018. Experimental design and experimental inference in stone artifact archaeology. J. Archaeol. Method Theory 25 (3), 663–688.
Loendorf, C., Blikre, L., Bryce, W.D., Oliver, T.J., Denoyer, A., Wermers, G., 2018. Raw material impact strength and flaked stone projectile point performance. J. Archaeol. Sci. 90, 50–61.
Lowe, C., Kramer, A., Wilson, M., Meindl, R., Spurlock, L., Eren, M.I., 2019. Controlled ballistics tests of ground, percussion-flaked, and pressure-flaked projectile point impact durability: Implications for archaeological method and theory. J. Archaeol. Sci.: Rep. 24, 677–682.
Maguire, L., Wilson, M., Buchanan, B., Eren, M.I., 2022. The Effect of Isometric Scaling on Flaked Stone Projectile Point Impact Durability. Lithic Technology.
Mika, A., Flood, K., Norris, J.D., Wilson, M., Key, A., Buchanan, B., Redmond, B., Pargeter, J., Bebber, M.R., Eren, M.I., De Smedt, P., 2020. Miniaturization optimized weapon killing power during the social stress of late pre-contact North America (AD 600–1600). PLoS ONE 15 (3), e0230348.
Odell, G.H., Cowan, F., 1986. Experiments with spears and arrows on animal targets. J. Field Archaeol. 13 (2), 195–212.
Pargeter, J., 2007. Howiesons Poort segments as hunting weapons: experiments with replicated projectiles. South African Archaeol. Bull. 62 (186), 147–153.
Scott, S.A., Davis, C.M., Flenniken, J.J., 1986. The Pahoehoe Site: A lanceolate biface cache in central Oregon. J. California Great Basin Anthropol. 8 (1), 7–23.
Sisk, M.L., Shea, J.J., 2009. Experimental use and quantitative performance analysis of triangular flakes (Levallois points) used as arrowheads. J. Archaeol. Sci. 36 (9), 2039–2047.
Thomas, D.H., 1986. Points on points: a reply to Flenniken and Raymond. Am. Antiq. 51 (3), 619–627.
Thomas, K.A., Story, B.A., Eren, M.I., Buchanan, B., Andrews, B.N., O'Brien, M.J., Meltzer, D.J., 2017. Explaining the origin of fluting in North American Pleistocene weaponry. J. Archaeol. Sci. 81, 23–30.
Titmus, G.L., Woods, J.C., 1986. An experimental study of projectile point fracture patterns. J. California Great Basin Anthropol. 8, 37–49.
Wadley, L., 2007. Announcing a still bay industry at Sibudu Cave, South Africa. J. Hum. Evol. 52 (6), 681–689.
Whittaker, J.C., Pettigrew, D.B., Grohsmeyer, R.J., 2017. Atlatl dart velocity: accurate measurements and implications for Paleoindian and archaic archaeology. PaleoAmerica 3 (2), 161–181.
Wilkins, J., Schoville, B.J., Brown, K.S., Chazan, M., 2012. Evidence for early hafted hunting technology. Science 338 (6109), 942–946.
Wilson, M., Perrone, A., Smith, H., Norris, D., Pargeter, J., Eren, M.I., 2021. Modern thermoplastic (hot glue) versus organic-based adhesives and haft bond failure rate in experimental prehistoric ballistics. Int. J. Adhes. Adhes. 104, 102717.