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North American Clovis Point Form and Performance: An Experimental Assessment of Penetration Depth

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ABSTRACT

In Late Pleistocene North America colonizing hunter-gatherers knapped and used Clovis fluted projectile points. During their expansion the size and shape of Clovis points changed significantly. Archaeologists know that cultural drift contributed to this variation, but is it possible that this single source could alone generate so much variation so quickly? We present the first of several experimental studies exploring whether Clovis size and shape variation results in performance differences, focusing here on how deeply different Clovis point forms penetrate a target. Our ballistics experiment demonstrates that seven different Clovis point forms penetrated the same target with different effectiveness. Even after tip cross-sectional perimeter is accounted for, there are significant differences in penetration depths between two of the point types. These results are consistent with the hypothesis that Clovis people in different times and places may have chosen specific attributes to provide them with a selective functional advantage.

KEYWORDS

Clovis; experimental archaeology; evolution; projectile technology

Introduction

When compared to the spread of other Pleistocene technologies, the rapid expansion and geographic reach of Clovis fluted points across North America is unprecedented (Bradley et al., 2010; Eren & Buchanan, 2016; Meltzer, 2009; Prasciunas & Surovell, 2015; Smallwood & Jennings, 2015; Waters & Stafford, 2007). The Clovis point not only spread quickly and extensively, but specimens in different places are broadly similar in terms of production technology (Eren et al., 2015a; Sholts et al., 2012; Smallwood, 2012; see also Bradley, 1993; Bradley et al., 2010; Collins, 1999; Morrow, 1995; Tankersley, 2004) and studies of stone raw materials suggest that Clovis people possessed broad social networks and territorial permeability (Boulanger et al., 2015; Buchanan et al., 2016; Ellis, 2008, 2011; Holen, 2010; Meltzer, 2009; Seeman, 1994; Speth et al., 2013). Even though Clovis population density was low, they maintained social connections with other groups to exchange information, resources, and mates for survival (Meltzer, 2002, 2003, 2004). This, however, raises the question: if Clovis technology or people with Clovis technology spread so quickly, Clovis networks were so extensive, and points were made with the same techniques, then why is there significant size and shape variation in Clovis point form over space, across time, and in different environments (Figure 1)? Given the temporal and spatial scale of the Clovis archaeological record, we presume cultural drift contributed to this variation, and several studies have supported this hypothesis (e.g. Buchanan & Hamilton, 2009; Eren et al., 2015a; Hamilton & Buchanan, 2009; Meltzer, 2009; Morrow & Morrow, 1999; O'Brien et al., 2014, 2016; Smallwood, 2012); but is it possible that this single source could alone generate so much variation so quickly? Or are multiple sources, for example contributions from both cultural drift + function, necessary to so rapidly give rise to such variety? Were Clovis people in different times and places choosing specific functional attributes of their points that would have provided them with a selective functional advantage? It is reasonable to predict that hunter-gatherers would have closely observed the performance of their technologies – what worked, what didn't, what is lasting longer than usual, and so on. Even if a technological mutation that improved a technology's function was not intended, further experimentation and positive

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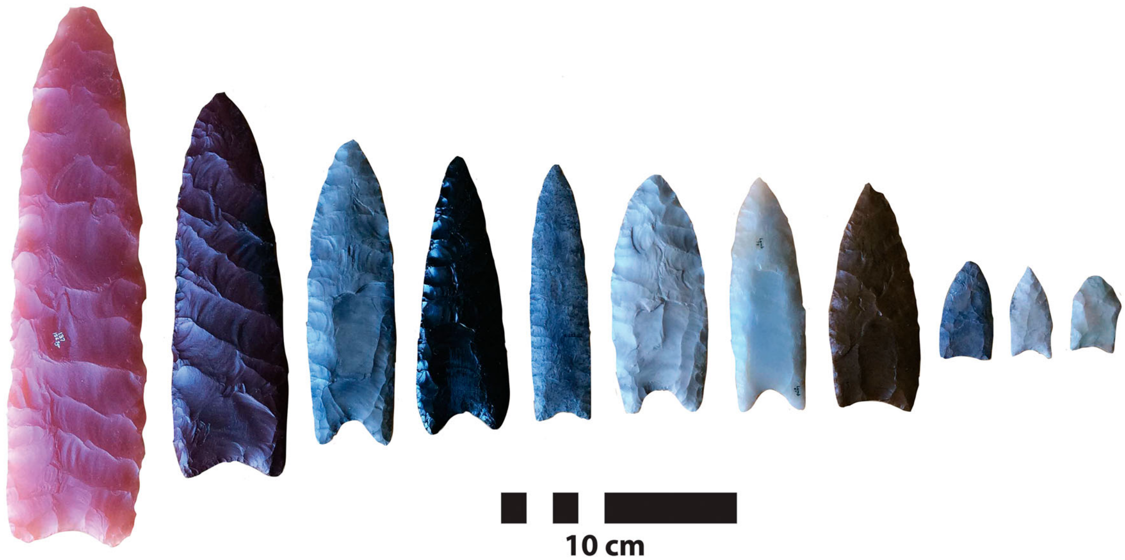

Figure 1. Clovis points across North America possess different forms (i.e. sizes and shapes).

performance feedback would have caused that mutation to be selected and ultimately fixed in a population's technological reperatoire (Thomas et al., 2017, p. 28).

Unfortunately, demonstrating whether or not that function played a role in the evolution and variation of Clovis points – or any other stone tool technology – can be challenging. This challenge primarily stems from the need to clear three analytical hurdles. To clear the first hurdle, what we term here *the variation problem*, requires quantitatively establishing the range of variation within a technology over space and time (e.g. Buchanan et al., 2014; Buchanan & Hamilton, 2009; Eren et al., 2016a; Lycett, 2008, 2009a, 2009b, 2011; Lycett & von Cramon-Taubadel, 2008; Morrow & Morrow, 1999; O'Brien et al., 2014, 2016; Smith et al., 2015). To successfully tackle this problem lithic analysts need to acquire and analyze (Lycett & Chauhan, 2010; O'Brien, 2010) large technological datasets spanning the geographic range and temporal period of the technology in question. The second hurdle to clear to make a case for function-based technological variation is what we term *the contribution problem* (Lycett & von Cramon-Taubadel, 2015). Lithic analysts now understand the fact that multiple sources of variation (both evolutionary and non-evolutionary) can combine and interact in ways such that technological variation is in reality the sum of these sources. To understand the role that function may or may not be playing in technological variation requires understanding whether and to what degree other factors may also be playing significant roles in that variation. Finally, to move beyond the final hurdle, what we term *the linkage problem*, requires direct, cogent behavioral linkage between technological variation and functional variation (Meltzer, 1991). As Odell and Cowan (1986, p. 195) suggested over 30 years ago, "Despite the undisputed importance of understanding the properties of essential variables, there has been a tendency among archaeologists to leap to higher-order interpretations without close attention to elemental observation." This means going beyond suggestions, assertions, or just-so stories of how a technology "is compatible with", or "may perform well in", specific circumstances, and instead empirically demonstrating via experiment a technological variant's functional advantages over other potential options (Eren et al., 2016b; Meltzer, 1991).

Thus, to support hypotheses asserting the role of function in technological variation we need to clear all three hurdles. If starting from scratch, this challenge may appear daunting, and could take years to successfully complete. But the North American Late Pleistocene Clovis archaeological record, specifically its fluted point component, is ideal to investigate the influence of function upon technology because the first two hurdles have been cleared as a consequence of the work of several researchers over the past two decades. So, to tease out the role function or performance characteristics in the form (size and shape) variation found in Clovis points, we need to clear the third and final hurdle: the linkage problem. That is what we present in this study.

The Clovis culture

The Clovis culture ("culture" *sensu* Mesoudi, 2011) is the earliest well-defined archaeological complex in North America dating to ca. 13,500–12,500 calendar years before present (calBP) (Anderson, 1990; Anderson & Gillam, 2000; Barton et al., 2004; Bradley et al., 2010;

Ellis, 2013; Eren & Desjardine, 2015; Gingerich, 2011; Haynes et al., 1984; Holliday, 2000; Holliday & Miller, 2013; Lepper, 2005; Levine, 1990; Miller & Gingerich, 2013; Steele et al., 1998; Waters et al., 2011a). The rapid geographic expansion of Clovis and its ubiquity across North America (Anderson & Faught, 2000; Anderson et al., 2005; Haynes, 1964; Meltzer, 2009; Prasciunas & Surovell, 2015; Sanchez, 2001; Waters & Stafford, 2007; Wormington, 1957), as well as the technology, mobility patterns, resource procurement, and site size and organization of its bearers, bespeak a continental human dispersal event unrestricted by earlier peoples (Andrews et al., 2015; Beck & Jones, 2010; Boulanger et al., 2015; Ellis, 2008, 2011; Eren, 2013; Eren & Andrews, 2013; Eren & Buchanan, 2016; Goebel et al., 2008; Goodyear, 1989; Hamilton & Buchanan, 2007; Haynes, 2002; Huckell & Kilby, 2014; Jennings et al., 2010; Kelly, 1999, 2003; Kelly & Todd, 1988; Kilby, 2015; Kornfeld et al., 2001; Meltzer, 2002, 2003, 2004, 2009; Morrow & Morrow, 1999; Prasciunas, 2007; Seeman, 1994; Seeman et al., 2013; Smallwood, 2010, 2012; Tankersley, 1994a; White, 2013, 2014). Despite disagreement over the existence, extent, and essence of "pre-Clovis" or "older-than-Clovis" peoples of North America (e.g. Adovasio & Page, 2002; Boulanger & Eren, 2015; Collins et al., 2013; Eren et al., 2013a, 2014b, 2015b; Fiedel, 2013; Halligan et al., 2016; Jenkins et al., 2012; Jennings & Waters, 2014; Meltzer, 2009; Morrow et al., 2012; O'Brien et al., 2014; Poinar et al., 2009; Sistiaga et al., 2014; Waters et al., 2011a, 2011b), the lack of fluted lanceolate stone points in the Old World suggests that the Clovis point probably emerged in the New World. If true, this suggests that there was at least a small "pre-Clovis" population present to innovate "the first American invention" before carrying or transferring it across the continent (Eren & Buchanan, 2016; Goebel et al., 2008; Krieger, 1954; Meltzer, 2009; Waters & Stafford, 2007).

There are two models for the timing and duration of the Clovis culture (Eren & Buchanan, 2016). The "short chronology" model suggests that Clovis lasted as little as 200–450 years, between 13,125 and 12,925 calBP or between 13,250 and 12,800 calBP (Waters & Stafford, 2007). The "long chronology" model suggests that the duration of Clovis could have been as long as 1500 years (Prasciunas & Surovell, 2015). Relative to global Pleistocene cultures and colonization events, both of these models are rapid.

Clovis points and point variation

Clovis points are bifacially-flaked specimens that have parallel to slightly convex sides, a concave base, and flake-removal scars – termed "flutes" – on one or both faces that extend on average from the base to about a third of the way to the tip (Eren & Buchanan, 2016; see also Bradley, 1993; Bradley et al., 2010; Frison & Bradley, 1999; Haynes, 1964; Meltzer, 2009; Waters et al., 2011b). Point flutes are visually distinctive, and archaeological and experimental studies suggest that they are costly to knap, often resulting in the breakage of the point (Meltzer, 1993b; Morrow & Morrow, 1999). The fluting process resulted in a thin and brittle base that may have served as a "shock absorber" upon point impact, redistributing stress and increasing point resilience for the purposes of avoiding breakage (Story et al., 2019; Thomas et al., 2017).

Clovis points could be produced either from raw nodules or from smaller flake-blanks of siliceous cryptocrystalline rock-types (Deller & Ellis, 2010; Eren et al., 2016c; Shott, 1993; Wernick, 2015), either directly at or nearby the parent stone source (e.g. Huckell et al., 2011; Lothrop, 1989; Sanders, 1990; Smallwood, 2010; Waters et al., 2011a, 2011b) or after the rock was carried for hundreds of kilometers (Boulanger et al., 2015; Buchanan et al., 2015; Ellis, 2011; Hoard et al., 1992, 1993; Holen, 2010; Kilby, 2014; Morrow, 1995; Seeman, 1994; Tankersley, 1989, 1994a). Clovis points often exhibit impact scars, which is strong observational evidence they were hafted and functioned as tips of thrusting and/or projectile weaponry (Kay, 1996). Current experimental and observational evidence of micro-fracture features on damaged fluted point tips suggests that Clovis hunters used spearthrowers (Hutchings, 1997, 2015). Successful experimental use of replica fluted points in penetrating the hide of deceased elephants is consistent with the idea that they could have similarly been used to inflict wounds on mammoths (Frison, 1989; Huckell, 1982). Clovis points have been found at archaeological sites associated with the remains of mammoth, mastodon, bison, and possibly a few other prey species (Grayson & Meltzer, 2015). Analysis of microwear on fluted points indicates that these items also served as cutting and butchery implements (Miller, 2013, 2014; Smallwood, 2015), also consistent with experiments (Frison, 1989; Gingerich & Stanford, 2016; Huckell, 1979).

Early stages of Clovis point manufacture used percussion flaking to strike well prepared, ground, isolated, and projected platforms (Bradley et al., 2010) to remove "overface" flakes (Smallwood, 2010), which are flakes that travel past the midline of the specimen and are the most efficient way to thin a stone biface (and occasionally result in overshot flake mistakes, see Eren et al., 2013a, 2014b). Additionally, these large overface flakes could themselves be turned into small points or other tools (Deller & Ellis, 2010; Ellis, 2008; Eren, 2013;

Prasciunas, 2007; Surovell, 2009; Wernick, 2015; Wilmsen, 1970). Finishing a Clovis point entailed a prehistoric knapper carefully removing the basal flutes as well as using pressure flaking to trim, straighten, and sharpen the edges (Bradley, 1993). Several observational and quantitative studies of Clovis point production strategies suggest that these specimens were made with similar production techniques across North America irrespective of geographic locality (Eren et al., 2011a, 2015a; Eren & Desjardine, 2015; Sholts et al., 2012; Smallwood, 2012; see also Bradley, 1993; Bradley et al., 2010; Collins, 1999; Morrow, 1995; Tankersley, 2004).

Although Clovis points appear to be made with the same production technology, numerous studies have documented differences in their form (size and shape) across North America (Anderson, 1990; Buchanan et al., 2014; Buchanan & Hamilton, 2009; Eren et al., 2015a; Hamilton & Buchanan, 2009; Meltzer, 1988, 1993a; Morrow & Morrow, 1999; Sholts et al., 2012; Smallwood, 2010, 2012; Smith et al., 2015; Storck & Spiess, 1994; Willig, 1991). What is not known is if these differences in form are due in some part to function. In other words, Clovis groups in distinct times and places may have chosen (not necessarily consciously) functional attributes of stone points that would have provided a selective functional advantage in capturing or processing prey, dealing with situational contingencies, and increasing overall tool resilience in local habitats. As early as 1952, Witthoft speculated that Clovis point differences might be due to function, stating they "appear rather as diverging traditions, each specializing somewhat in a different direction". More recently Buchanan et al. (2014) suggested that the shape of Clovis points across the continent is regionally patterned, perhaps suggesting that shape was adapted to the environmental differences between these regions.

How much, if any, of the form differences documented in Clovis points is linked to function is currently unknown. To investigate and answer this question, we examine this question through the lens of the three hurdles described above: the variation problem, the contribution problem, and the linkage problem.

The variation problem

In order to make a strong case that Clovis point form differences are due to function, we need to first know that there is significant variation of Clovis point size and shape across space and time. While variation in Clovis point form has been acknowledged for some time (e.g. Mason, 1962; Meltzer, 1993a; Witthoft, 1952), only in the past 20 years has this variation been quantified and subject to robust statistical analysis. The use of ratios by Morrow and Morrow (1999) and inter-landmark distances by Buchanan and Hamilton (2009) showed that aspects of Clovis point morphology varied over space, while Smallwood (2012) found morphological variation in point form amongst sub-regions of Southeastern North America. More recently, Buchanan et al. (2014) and Smith et al. (2015) demonstrated statistically significant differences exist between point shape and particular regions. These latter studies employed a powerful suite of shape analysis methods from biology called geometric morphometrics (GM) to measure a large sample of points from Clovis assemblages across North America. Using discriminant function analysis (DFA) and significance tests, Buchanan et al. (2014) found points from Western and Eastern North America were significantly different. They also found that Clovis points from the Northeast were significantly different from those of three other Eastern subregions and that within the West, points from the Northwest were significantly different from those from the Southern Plains and Southwest, and Northern Plains points were different from Southern Plains points. The work of Smith et al. (2015) was consistent with these findings, especially for Clovis points from the Northeast. In sum, the first hurdle, the variation problem has been cleared.

The contribution problem

In order to make a strong case that Clovis point form differences are due to function, we also need to understand the role that non-function and non-heritable factors are playing. With respect to non-functional factors, several studies have now shown that stochastic mechanisms (i.e. cultural evolutionary drift) played a significant role in Clovis point form. Morrow and Morrow (1999) attributed the "incremental" changes of Clovis point metric ratios across North America to drift (see also Meltzer, 2009); a result Buchanan and Hamilton (2009) supported a decade later with more robust inter-landmark morphometrics and statistical analyses. Focusing specifically on size, Hamilton and Buchanan (2009) demonstrated that Clovis points across North America decreased in size at a rate predicted by the Webber fraction, "suggesting that spatial variation in Clovis projectile point size is due to drift processes caused by the accumulation of copying errors over multiple transmission events". Most recently, Eren et al. (2015a) conducted geometric morphometric analyses of Clovis points from three distinct stone outcrops within a single, small region – the eastern riverine subarea of the unglaciated midcontinental United States (see Lepper, 2005; Tankersley, 1989) – in a study that controlled for environment. The three point samples possessed significantly different shapes, but because the analysis was both intra-regional and because points from the different outcrops were being used to exploit overlapping areas within that same small environment, the differences could not be attributed to function, but only to drift. Together these analyses suggest that if function is playing a role in Clovis point form, it is in addition to, not instead of, stochastic evolutionary mechanisms and that some point traits may have been under the control of function, while others were subject to drift (Hamilton & Buchanan, 2009, p. 67; see also Bentley, 2007; Bentley et al., 2004, 2007; Brantingham, 2003; Eren et al., 2015a; Kuhn, 2012; Lycett, 2008; Lycett & von Cramon-Taubadel, 2015).

In addition to cultural evolutionary drift there are two important developmental or ontogenetic factors that could potentially contribute to Clovis point shape differences across the continent: differential raw material constraints and differential amounts of resharpening (e.g. Haynes & Huckell, 2007; Miller & Gingerich, 2013; Tankersley, 1994b; Thulman, 2012; White, 2013). With respect to the raw material differences, it should be noted that Clovis points are overwhelmingly knapped on, from the modern archaeologist's perspective, "high quality" stone raw materials such as fine-grained chert, chalcedony, or jasper, as well as non-siliceous but exceedingly knappable stone such as obsidian (Buchanan et al., 2016). Additionally, several preliminary or post-hoc evaluations from previously discussed Clovis point studies have ruled out raw material differences as a predominant, or even significant, factor in Clovis point variation (Buchanan et al., 2014; Buchanan & Hamilton, 2009; Eren et al., 2015a; Smallwood, 2012). Finally, there is now a growing global consensus from archaeological and experimental evidence that the hypothesis that lithic raw material necessarily determines artifact form cannot be supported (Archer & Braun, 2010; Bar-Yosef et al., 2012; Brantingham et al., 2000; Clarkson, 2010; Costa, 2010; Ditchfield, 2016; Eren et al., 2011b, 2014a; Gurtov et al., 2015; Gurtov & Eren, 2014; Lycett & von Cramon-Taubadel, 2015; Mraz et al., 2019; Sharon, 2008; Wang et al., 2012).

With respect to differential amounts of Clovis point resharpening across North America, this factor too appears to be subsidiary in its influence on overall Clovis point form at the assemblage level. Like raw material, point resharpening has been examined in several analyses and shown to be negligible in its impact, again at the assemblage level (Buchanan et al., 2014; Buchanan & Collard, 2010a, 2010b; Buchanan & Hamilton, 2009; Eren et al., 2015a; Smallwood, 2012). Shott's (2010) comparative analysis of Clovis to post-Clovis points revealed that the latter showed greater evidence of resharpening relative to the former. More recently, Buchanan et al. (2015) used a large sample of Clovis points from the midcontinent and statistically examined the currently accepted markers of resharpening, namely point size, shape, and scar patterning, and analyzed these markers in relation to each other as well as to distance to stone source. Their results indicated that resharpening was not a significant source of Clovis point variation at the assemblage level. Beyond this, several observational studies have now demonstrated that small Clovis points assumed to have been extensively resharpened (hence their small size) were actually knapped on small flake-blanks to begin with, as opposed to large chert nodules (Deller & Ellis, 2010; Eren et al., 2016c; Shott, 1993; Wernick, 2015). None of this is to say that individual Clovis points were not resharpened and that the resharpening may potentially have altered their shape (although even at the individual specimen level, resharpening may not have had an impact. For example, Smallwood (2010, p. 2414) notes that even when Clovis points were resharpened "their standard shape was maintained during use and resharpening events, through which a point typically could be reduced to a length of less than 50 mm"). Instead, the consensus of these Clovis point resharpening analyses is that the presence of individual resharpened points does not currently appear to skew or overwhelm stylistic signals on the assemblage level, especially since the process of resharpening itself may be culturally patterned (Buchanan et al., 2015; Eren & Prendergast, 2008; Ioviță, 2010; Lycett & von Cramon-Taubadel, 2015).

In sum regarding non-heritable factors, following Morrow and Morrow (1999, p. 219), it is important to acknowledge the role of raw material and resharpening, and to note that they may potentially introduce a small and unspecified amount of variation in the data. Yet, there is no evidence to support the idea that they are substantially or significantly confounding or skewing overall geo-temporal trends of Clovis point form across North America.

The linkage problem

Finally, in order to make a strong case that function contributed to Clovis point form differences across North America, we need to make direct, cogent behavioral linkage between functional and technological variation (Buchanan et al., 2014; Eren & Buchanan, 2016; Meltzer, 1991; Mika et al., 2020; Odell & Cowan, 1986). For example, it has long been proposed that different point forms are connected with the type of prey targeted by Clovis hunters in different regions and sub-regions (Buchanan et al., 2011). Indeed, zooarchaeological evidence suggests western Clovis is associated with mammoth and bison whilst eastern Clovis is associated with smaller, more diverse game (Cannon & Meltzer, 2004; Storck & Spiess, 1994). Thus, a compelling motivating factor linking technological differences directly to function would be increased penetrability for western Clovis point form in order to slice through thicker prey hides (Buchanan et al., 2014). Similarly, given differences in fauna in distinct North American regions and the need for people to process these items via cutting or butchery, as well as the fact that microwear analysis suggests Clovis points were used as knives, perhaps different Clovis point forms possess different levels of cutting efficiency, or robustness during cutting tasks. In one final example, it is reasonable to propose that Clovis points found in more open Western environments possessed forms that were more aerodynamic relative to those found in the more forested Eastern environments (Buchanan et al., 2014), whereas Clovis points found in the forested East possess forms more durable upon impact given the increased chance of hitting trees.

When viewed in aggregate, the examples in the previous paragraph point to the fact that if function played a role in Clovis point form differences across North America, then there should be differences in task performance among distinct point forms. How can we determine the relative functionality, efficiency, and effectiveness of different Clovis point forms in performance tasks and move beyond the current "interpretive stalemate" (Shea et al., 2001, p. 808) of function's contribution to those differences? Lithic analysts, especially those focusing on stone weaponry and projectile technology, have long used experiments involving replica points to understand the performance characteristics of archaeological ones (see references and discussion in Eren et al., 2016b and Knecht, 1997; see also Bergman & Newcomer, 1983; Broglio et al., 1993; Cheshier & Kelly, 2006; Christenson, 1986; Fischer, 1985; Frison, 1989; Huckell, 1982; Hunzicker, 2008; Hutchings, 1997, 2011, 2015; Iovita et al., 2014; Lipo et al., 2012; Lombard et al., 2004; Lombard & Pargeter, 2008; Odell & Cowan, 1986; Pettigrew et al., 2015; Sano & Oba, 2015; Shea et al., 2001; Sisk & Shea, 2009; Smith et al., 2007; Titmus & Woods, 1986; Waguespack et al., 2009; Whittaker, 2010, 2013; Whittaker & Kamp, 2006; Whittaker & Maginniss, 2006; Whittaker & McCall, 2001; Wilkins et al., 2012, 2014), and that is what we are presenting here. By undertaking a multi-year, multi-function experimental assessment, we have investigated numerous performance tasks of different Clovis point forms to tease out whether different forms perform differently.

There are many potential performance attributes to explore, however, and our focus in this first manuscript is projectile point penetration depth, a critical factor for killing prey (Cheshier & Kelly, 2006; Clarkson, 2016; Friis-Hansen, 1990; Guthrie, 1983; Hughes, 1998; Loendorf et al., 2017; Mika et al., 2020; Pargeter, 2007; Salem & Churchill, 2016; Shea et al., 2002; Tomka, 2013; Waguespack et al., 2009; Wood & Fitzhugh, 2018). Our null and alternative hypotheses are simple and straightforward. If function did not contribute to different Clovis point designs, then we can predict that there will be no differences in penetration depth among Clovis points of different form. The implication of this result is that stochastic mechanisms (i.e. cultural evolutionary drift) were predominately responsible for the significant variation of Clovis points across the continent (Hamilton & Buchanan, 2009; Meltzer, 2009; Morrow & Morrow, 1999). Given the speed with which Clovis points spread across the continent, this result would also have implications for how quickly cultural drift can occur in stone tool technology to cause significant variation (Eren et al., 2015a), even amongst sparse forager populations who must maintain tight social networks to survive (Buchanan et al., 2016; Meltzer, 2002, 2003, 2004, 2009). Finally, this result would suggest that the Clovis point bauplan was flexible enough to function well in North America's diverse landscapes and/or that not enough time had elapsed during the Clovis period for function to cause adaptive changes in point form (Buchanan & Hamilton, 2009; Morrow & Morrow, 1999). Thus, this result would be consistent with the idea that it was not until post-Clovis periods that points were potentially adapted to specific functions (e.g. White, 2013), although this would need to be tested in future experiments.

Alternatively, if function contributed to Clovis point design, then we can predict that there will be significant differences in penetration depth among one or more Clovis point forms (Buchanan et al., 2014). The implication of this result is that the significant differences in Clovis point form across North America were potentially a result of contributions from both function and cultural drift. This result would be consistent with the idea that sparse Clovis populations selected the attributes of their points that would have provided them the best chance for effectiveness and efficiency in tool related tasks such as hunting and butchery.

Materials and methods

Defining Clovis projectile point shape variation and selecting models

For this study we selected seven Clovis points representing the extreme bounds of known Clovis point shape to replicate in stone and use in our experiments. To find the extremes of Clovis point shape we used the large sample (n=241) of Clovis points from Buchanan et al.'s (2014) study. This study examined Clovis points from well-documented Clovis assemblages from sites geographically spanning most of North America. A set of 23 landmarks was used to delineate the outlines of Clovis points in this sample and geometric morphometric methods were employed to extract shape variables from this landmark dataset (see Buchanan et al., 2014 for a full description of the methods and procedures carried out). To find the extreme point shapes to replicate we conducted a principal components analysis (also termed a relative warp analysis) which resulted in fewer variables than the original shape dataset (n=46) comprising most of the shape variation in the data.

Specifically, we concentrated on the first three relative warps, which accounted for over 93% of the overall shape variation (Figure 2). We then found the specimens with the lowest and highest relative warp scores for each of the first three components. On the first axis, PC1, the highest score on the first relative warp was 0.1937 which corresponds to a point from the Simon assemblage found in Idaho, and the lowest score on the first relative warp was −0.2368 which corresponds to a point from the Shoop assemblage found in Pennsylvania. The shape variation along this axis primarily relates to the width of points, with narrow points on the positive end of the PC1 axis and wide points on the negative end of the PC1 axis. On PC2, the maximum score of 0.056 also corresponds to a point from the Shoop site (although a different point than the Shoop point on PC1) and the minimum score on PC2 is a point from the Vail assemblage in Maine. The shape variation along this axis goes from points with flat bases on the positive end to points with deeply indented bases on the negative end of PC2. The point with the maximum score on the PC3 axis is from Anzick in Montana and the minimum PC3 score is from Rummells-Maske in Iowa. The shape variation on this third axis involves the location of maximum width. Points on the positive end are triangular with their maximum width near the base and points on the negative end have their maximum width closer to the tip and are more ovate in shape. In addition to the extremes, we replicated the point closest to the center of the three-dimensional distribution. The point at the center is lanceolate in form and from the Bull Brook site in Massachusetts. Together these six specimens and the point that was found closest to the origin of the three axes comprise the seven replica points used in the experiment.

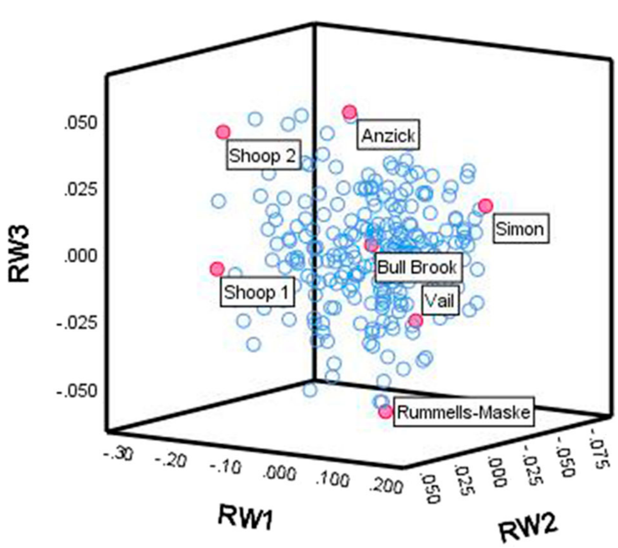

Figure 2. Relative warp analysis of the two-dimensional Clovis point shape variation. The first three relative warps (RW1, RW2, and RW3) represent 93% of the overall shape variation in the dataset. The red-filled triangles represent the points at the extreme ends of the three axes and the center of the distribution, while the open blue circles represent other Clovis points.

The seven replica Clovis points defining the empirical shape variation in the Clovis dataset also possess substantial geographic and size variation (Figures 3 and 4).

Production of stone models

Seven types of Clovis projectile point were produced by Neolithics Flintknapping Supply House (www.neolithics.com) using Texas Fredericksburg chert (Figure 4a) (see also Sitton et al., 2020). First, slabs of chert were cut out with a rock saw, put in a kiln, and heat-treated to 450 degrees. Then a pattern for each particular point shape was drawn on the slabs and cut out with a trim saw. Next, each point-shaped slab was rough ground with a 30- and, subsequently, a 60-grit diamond wheel, to produce a typical stone tip's lenticular shape. Table 1 presents the experimental point measurements.

Hafting of stone models

The projectiles were hafted by Thunderbird Atlatl (www.thunderbird.com) (Figure 4b). Each stone tip was hafted to a 1/2 inch ash dowel manufactured in Thunderbird Atlatl shop. The dowels were milled to fit the various sizes of stone points. Hemp fiber and Kodak gelatin based glue dissolved in warm water was used for hafting the projectiles on to the dowels. A small electric heated glue pot was used to maintain the correct viscosity of the glue. The method for attaching the stone points was to first shape the wood to fit the point. The wood and the stone points were dipped into the glue pot. Next, a measured amount of fiber was dipped into the glue pot. The glue was spread evenly on the fiber

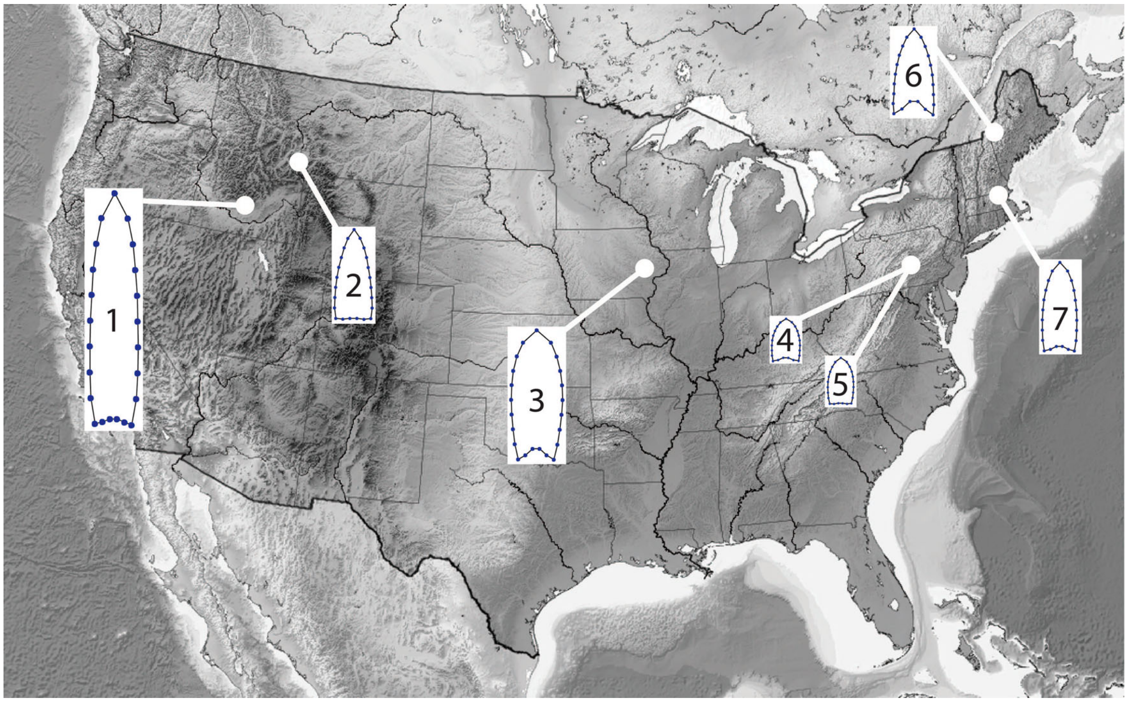

Figure 3. Our seven Clovis experimental points were based off of points from Simon (1), Anzick (2), Rummells-Maske (3), Shoop (4,5), Vail (6), and Bull Brook (7). Not only do these points possess different forms (sizes and shapes), they also are geographically variable.

and then wrapped over the wood/stone joint by hand. Care was taken to make sure that there was a good connection free from voids. The glue was allowed to dry for 24 h, inspected, then packaged for delivery. Table 1 presents the measurements related to hafting.

Experimental procedures

Our experiment here was akin to other ballistics studies performed at the Kent State University Experimental Archaeology Laboratory, a controlled indoor setting (Figure 5) (Bebber et al., 2020; Bebber & Eren, 2018; Key et al., 2018; Lowe et al., 2019; Mika et al., 2020; Sitton et al., 2020; Werner et al., 2019). We shot the seven hafted experimental Clovis points with a 29 lbs. PSE compound bow mounted on a Spot-Hogg Hooter Shooter.

We used a stationary target, which was approximately 1.8 meters from the compound bow. We fired the hafted specimens into blocks of moist clay containing crystalline silica, which has been used as an ethical substitute for meat and tissue in other studies (Bebber et al., 2020; Caranta & Legrain, 1993; Key et al., 2018; Key & Lycett, 2017; McGorry, 2001; McGorry et al., 2004; Mika et al., 2020). With respect to target penetration depth, each of the seven Clovis projectile point forms was shot into the clay target thirty times. We measured penetration depth by holding the shaft at the location at which the shaft was first exposed in the clay target. After removal of the projectile from the target, we measured the distance from the person's fingers to the tip of the point.

We did not control for velocity in our experiment. Instead, each projectile was pulled to a standardized bow draw length of 48 cm (Sitton et al., 2020). This procedure was selected because a prehistoric person would not have been able to produce more energy to achieve a greater velocity with a heavier point, nor would they have necessarily used less energy to achieve a slower velocity with a lighter point (Sitton et al., 2020). Our velocity data thus reflect that – given a single hypothetical individual firing all seven forms – the more massive projectiles travel slower than the smaller ones. To measure velocity, we used a Gamma Master Model Shooting Chronograph throughout the experiment. The Chronograph readings on occasion result in "error" if there is a change in sunlight, cloud cover, or some other minor variable. As a result, we recorded a percentage of 30 possible stone point velocity readings per point type (Table 2; DATA S1). We note that the velocities produced in our experiment fall well within the range of human atlatl throwing velocities (Whittaker et al., 2017).

Statistical analysis of penetration depths

We examined penetration depths (n=30) associated with the seven Clovis point forms representing the three primary principal components of shape variation in the overall Clovis point shape distribution described above.

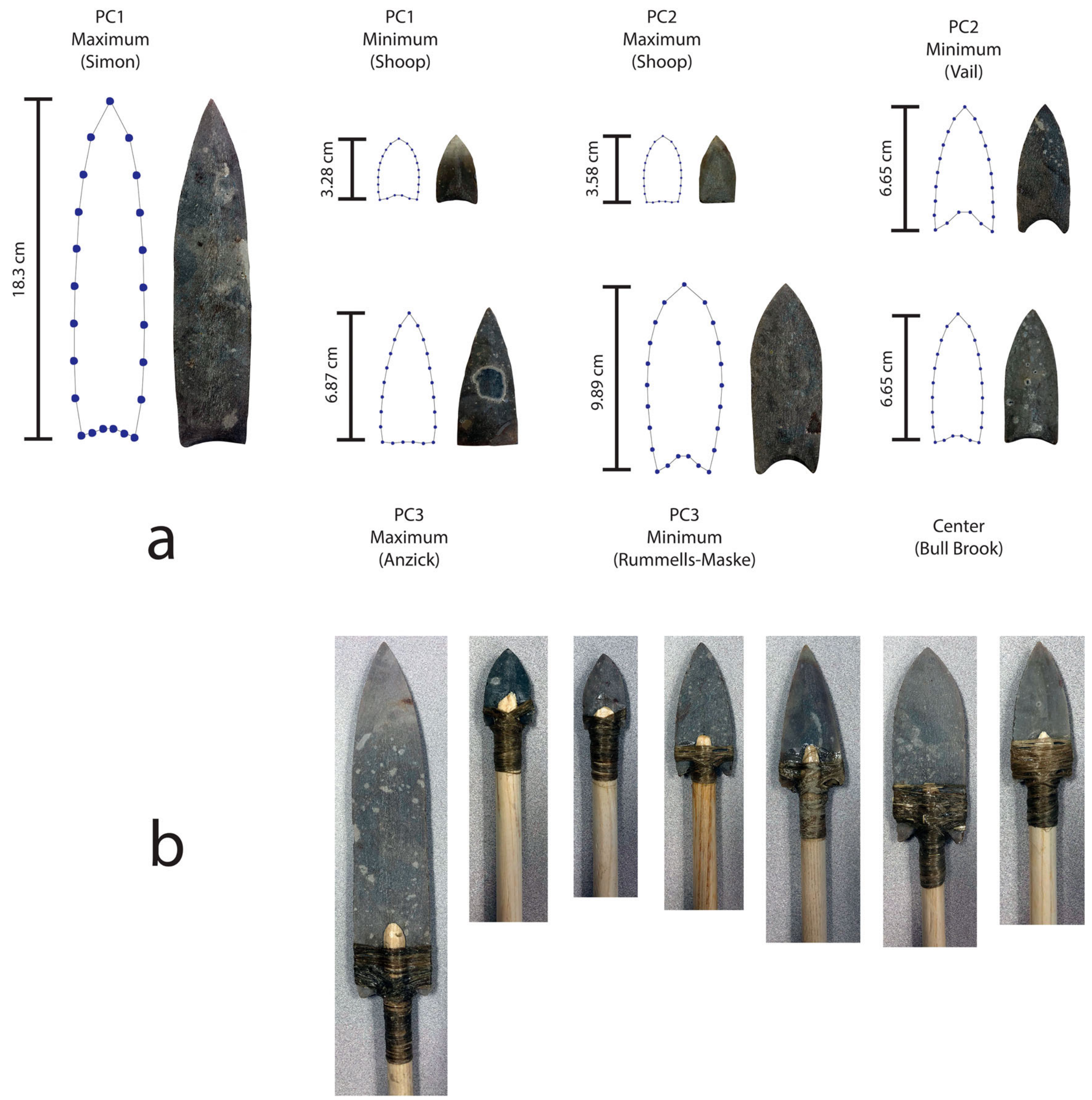

Figure 4. The morphometric outline and experimental stone counterpart of the seven Clovis point forms (a). The seven point forms are from Simon (PC1 max, long and narrow); Shoop (PC 1 min, short and wide); Shoop (PC 2 max, short and flat base); Vail (PC 2 min, deep base); Anzick (PC 3 max, triangular); Rummells-Maske (PC 3 min, ovate); and Bull Brook (center; lanceolate). Each of the seven experimental stone points hafted (b).

To reiterate, these points, although selected based on shape variation, also represent substantial geographic and size variation. We first present summary statistics of the penetration depths for each of the replica points in the experiment. We then conducted tests of statistical normality of each set of penetration depths using Shapiro–Wilk tests to determine if parametric or non-parametric analyses were required. Following these tests we conducted nonparametric Kruskal–Wallis tests on the set of penetration depth measures to determine if there is a statistical difference in median penetration depth across the types. Subsequently, we conducted Mann–Whitney tests with Bonferroni-controlled *p*-values to determine which pairs were significantly different from each other.

Following the overall Kruskal–Wallis test we did an additional set of tests examining penetration depth while including point tip cross-section perimeter (TCSP) in our model. TCSP is calculated as:

$$\text{TCSP} = 4\sqrt{\left(\frac{w_{tip}}{2}\right)^2 + \left(\frac{t_{tip}}{2}\right)^2}$$

where w_{tip} and t_{tip} are the width and thickness, respectively, of the point measured at the widest location on the point. A number of studies have shown analytically that penetration depth is inversely proportional to TCSP (Ashby, 2005; Bestul & Hurteau, 2015; Hughes, 1998; Kneubuehl, 2011; Mika et al., 2020) and controlled experimental work has further verified this (Sitton et al., 2020).

Table 1. Experimental projectile measurements. Note that point lengths differ slightly from Figure 4 because hundreds of points of each type were produced.

Projectile	Point type	Total projectile mass (g)	Point length (mm)	Point width (mm)	Point thickness (mm)	Haft binding length (mm)	Haft binding width (mm)	Haft binding thickness (mm)	Shaft length (cm)	Shaft diameter (mm)
1	Simon	139.30	185.00	40.76	7.06	47.40	41.78	16.56	71.00	12.95
2	Shoop 1	55.60	34.84	21.26	5.83	35.49	21.97	13.61	71.20	11.41
3	Shoop 2	62.40	36.00	20.32	4.90	26.90	20.98	13.41	71.30	11.97
4	Vail	69.90	66.67	28.76	5.25	24.25	31.21	13.58	71.70	12.06
5	Anzick	64.70	70.38	25.65	5.60	24.24	31.72	13.68	71.30	11.41
6	Rummells-Maske	85.90	95.58	37.81	6.87	38.73	35.53	15.12	70.80	11.76
7	Bull Brook	63.90	64.48	25.31	5.76	40.92	28.58	14.69	71.20	11.90

Note: There was minor production variation present in these specimens. For this experiment we selected only one specimen of each type, and the point measurements of those specimens are presented here. Total projectile mass is the point + shaft + binding. In this, and all tables, Shoop 1 refers to the PC1 minimum form, and Shoop 2 refers to the PC 2 maximum form.

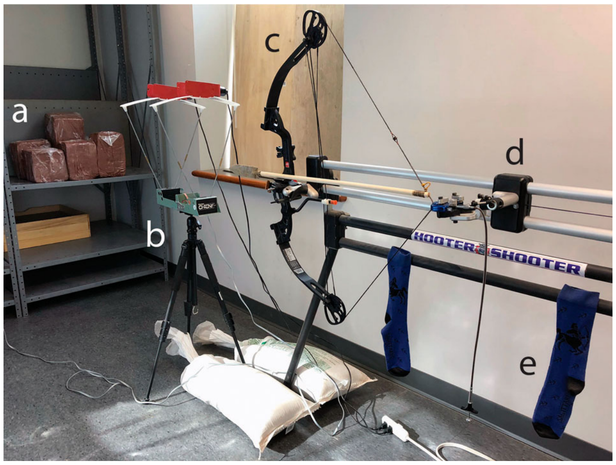

Figure 5. The experimental set-up included large blocks of clay (a); a Gamma Master Model Shooting Chronograph (b); a PSE compound bow (c); a Spot-Hogg Hooter Shooter (d); Sagittarius bow hunting socks for good luck (e).

We tested the influence of point form and TCSP on penetration depth using a hierarchical, unequal variance, Bayesian regression model implemented in R 3.6.1 (R Core Team) with the *brms* package. This approach was selected to adjust for the 30 repeat sample experimental firings within each point form. Weak prior probability distributions (priors) were assigned to all parameter values to ensure model fit. The TCSP slope was assigned a normal (mean = 0, SD = 10) prior, and intercepts and standard deviations of the grouping effect were assigned student *t* (df = 3, mean = 0, SD = 10) priors. Final models were run with 4 chains for 10,000 iterations. For all parameters $\hat{r}$ values (a model diagnostic with expected value equal to 1) were below 1.01 to ensure model convergence. Chains were inspected visually for sufficient mixing to ensure that model results were appropriate. The model has an R-sq of 0.69. (Unfortunately, even though we had intended for profile view to be controlled, the reality of production did not match our intentions. The points larger in plan-view were also slightly thicker than the points smaller in plan-view. Thus, to be on the safe side, it was important to control for TCSA.)

Results

The summary statistics for the penetration depths for the seven Clovis points in our experiment are presented in Table 3. The deepest penetration depths are associated with the two points from Shoop, whereas the long Simon point had the shallowest average penetration. Normality tests indicate that only the second Shoop point's sample does not conform to an underlying normal distribution (Table 4). Given this result we conservatively used nonparametric Kruskal – Wallis tests, however, the results are qualitatively similar to the parametric analyses. The results of the Kruskal–Wallis test are highly significantly different (Hc [tie corrected]=151.7, p<0.00).

Subsequent analyses, including Mann–Whitney and Tukey's Q comparisons, show that four pairs of point forms have statistically similar penetration depths, all

Table 2. Velocity summary statistics.

Projectile	Site	Velocity sample size	Mean velocity (m/s)	Standard deviation	Minimum velocity	Q1	Median	Q3	Maximum
1	Simon	19	22.85	2.68	20.70	21.70	22.12	22.49	30.55
2	Shoop 1	12	33.46	4.93	22.39	35.27	35.57	35.83	36.08
3	Shoop 2	22	34.25	1.98	29.84	33.46	33.75	34.01	38.42
4	Vail	23	32.15	1.11	31.07	31.66	31.99	32.22	37.08
5	Anzick	16	33.38	0.39	32.28	33.28	33.41	33.58	33.94
6	Rummells-Maske	18	28.86	0.20	28.47	28.72	28.83	29.01	29.18
7	Bull Brook	20	34.29	1.97	32.55	32.96	33.46	34.66	37.95

Table 3. Summary statistics of the penetration depths for the seven replica Clovis points.

	Simon	Shoop 1	Shoop 2	Vail	Anzick	Rummells-Maske	Bull Brook
Mean	14.27	21.88	22.91	18.37	17.87	16.28	18.63
Median	14.05	21.7	22.35	18.2	18.2	16.45	18.5
Minimum	11.6	15.5	19.1	15.3	14.5	13.5	15.1
Maximum	16.9	26.3	28.6	23.4	20.3	18.4	23.5
Stand. dev	1.37	2.36	2.42	1.93	1.32	1.14	1.89
CV	9.63	10.77	10.55	10.49	7.36	7.01	10.15

Note: Measurements are in centimeters.

Table 4. Results of Shapiro-Wilk tests for normality in the penetration depth data for each replica Clovis point.

	Simon	Shoop 1	Shoop 2	Vail	Anzick	Rummells–Maske	Bull Brook
Shapiro-Wilk W	0.958	0.959	0.907	0.955	0.963	0.968	0.982
p	0.2720	0.2921	0.0124	0.229	0.3697	0.4868	0.8698

Table 5. Lower triangle of matrix is results of the Mann–Whitney Bonferroni-Corrected pairwise comparisons of penetration depths for replica Clovis point forms (the upper triangle is Tukey's Q multiple comparisons).

	Simon	Bull Brook	Shoop 1	Shoop 2	Vail	Rummells–Maske	Anzick
Simon		0	0	0	0	0.001	<0.000
Bull Brook	<0.000		<0.000	0	0.998	<0.000	0.676
Shoop 1	<0.000	<0.000		0.3073	<0.000	0	<0.000
Shoop 2	<0.000	<0.000	1		0	0	0
Vail	<0.000	1	<0.000	<0.000		<0.000	0.9384
Rummells–Maske	<0.000	<0.000	<0.000	<0.000	<0.000		0.016
Anzick	<0.000	1	<0.000	<0.000	1	<0.000	

other pairs are significantly different (Table 5). The similar pairs include the two points from Shoop, the point from Bull Brook and the points from Vail and Anzick, and the Vail and Anzick points. The Simon point exhibits significantly less penetration depth than the other point forms. Rummells-Maske has on average greater depths than Simon, but penetrated significantly less than the other point forms. Anzick is similar to Vail and Bull Brook, shows deeper penetration than Simon and Rummells-Maske, and less than both Shoop forms. Penetration depths for Bull Brook and Vail are similar to each other and to Anzick, but are greater compared with Simon and Rummells-Maske and less than both Shoop points. While penetration depths for both Shoop points are similar to each other, they are deeper compared with the other point forms.

TCSP has a strong negative effect on penetration depth, as expected (slope = −0.17, 95% credible interval = −0.27, −0.05) (Figure 6; see also Sitton et al., 2020). But, controlling for TCSP, penetration depth still varied somewhat with point form. Figure 7 shows the posterior distributions after controlling for TCSP. The least penetration on average was seen in Anzick points (estimate = −1.73, 95% credible interval = −3.38, −0.18). Anzick points had the only estimate that differed significantly from zero. The most penetration on average was seen in the second Shoop point (estimate = 1.27, 95% credible interval = −0.84, 3.85), but this credible interval includes zero as did all the other point types other than Anzick. We can infer that the second Shoop point had significantly greater penetration than Anzick, and that all the other point types were intermediate with overlapping distributions between these two.

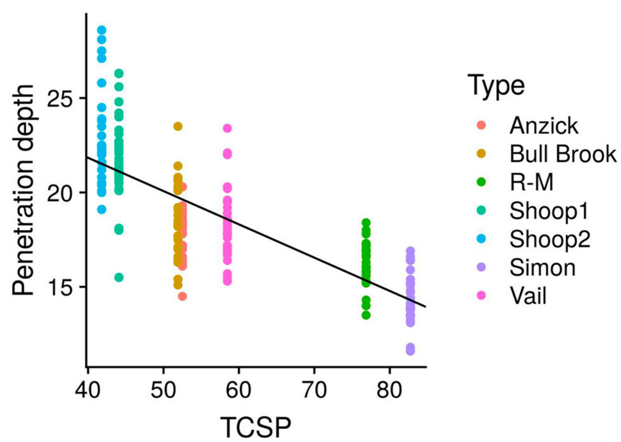

Figure 6. Bivariate plot of Clovis replica point tip cross-section perimeter and penetration depth with Ordinary Least Squares best fit line in red (slope=−0.17). Penetration depth is measured in centimeters.

Discussion

The focus of our experiment presented here was on one functional aspect of stone point performance,

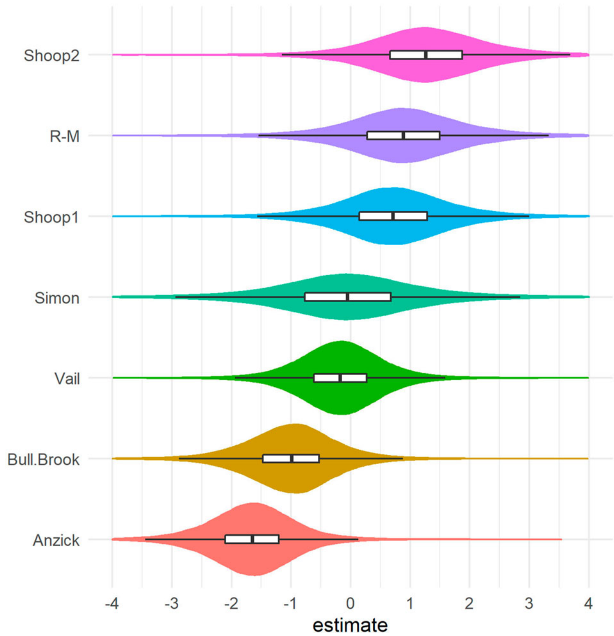

Figure 7. Violin plot of the posterior distributions after controlling for TCSP.

penetration depth. Penetration depth is particularly important as it both increases the probability of impacting major organs, and decreases the probability of a projectile becoming dislodged in a wounded animal. The controls of the experiment allowed us to isolate this single functional outcome and compare it among seven different replica forms of actual Clovis points representative of the shape and size variation exhibited in Clovis points from different regions of North America.

The results of our first set of analyses show that several of the Clovis point forms exhibit statistically different penetration depths. This analysis demonstrated that for a constant input energy and the range of velocities observed, larger points from Clovis caches, including Simon, Rummells-Maske, and Anzick, exhibit shallower penetration depths, while the smaller points from the Shoop site penetrate much deeper. Overall, points from the eastern areas, including both Shoop forms, Bull Brook, and Vail, have deeper penetration depths when compared with the points from more western areas as eastern Clovis points are on average smaller than western Clovis points.

These results are consistent with the hypothesis that Clovis point form variation is the result of contributions from both function and cultural drift. While Clovis point form evolved via stochastic mechanisms as sparse populations moved across the continent (Eren et al., 2015a; Hamilton & Buchanan, 2009; Morrow & Morrow, 1999), our results showing that different Clovis point forms perform differently in terms of target penetration suggest that functional attributes may have also been selected, further influencing point form (Buchanan et al., 2014).

Future experiments we report upon will examine other functional considerations, such as point durability, haft durability, aerodynamics, and butchery. Thus, while Clovis point forms varied in terms of penetration depth, they may exhibit other functional advantages. As each set of task performance experiments is completed, we will be able to discuss the advantages, disadvantages, and functional compromises of different point forms, which can then be applied to regional point form tendencies or point form variation within sites.

In future experiments, it will be important to relax the assumption of constant input energies and target resistances. For example, it will be important to understand how penetration is impacted by point size and velocity across a range of hide thicknesses (and therefore body sizes). Additionally, it will be important to understand how the variation of penetration depths within a given type is impacted by the range of possible velocities given the physics of the delivery systems over a range of distances, and likely the variation of the strength and skill of the users. While future analyses will be designed to tease out these influences on penetration depth, our results show that TCSP has a strong relationship with penetration depth (see also Sitton et al., 2020). These results are interesting because, as demonstrated by Hamilton and Buchanan (2009), Clovis points get increasingly smaller – and necessarily possess smaller TCSP values – over time and from west to east. The Clovis point size decreases documented by Hamilton and Buchanan (2009, p. 67) were consistent with the Weber fraction, suggesting that variation in projectile point size could be due to drift processes caused by the accumulation of copying errors over multiple transmission events. Yet, they emphasized that their results did not suggest that "directional selection never occurred" (Hamilton & Buchanan, 2009, p. 67). Our results suggest that it is plausible that Clovis people selected for performance criteria – in this case decreased TCSP and increased penetration depth – over time and across space. To paraphrase Bebber et al. (2017, p. 79), although we now know smaller points would have a provided benefit to Clovis hunters, the ultimate source of that functional benefit, drift or selection, is currently difficult to pin down.

To begin this examination, we performed a Bayesian analysis to evaluate differences in penetration depth while simultaneously accounting for the influence of TCSP. We did this to examine if any residual aspects of point form – especially involving plan-view form – might have functional significance. Indeed, the results show that while there is much overlap, at least two point forms, the triangular-shaped point from Anzick and the short second Shoop point with a flat base, have different penetration capabilities. The triangular Anzick point has significantly less penetrating ability than the second Shoop point. By controlling for TCSP, these results are consistent with the notion that the 2d plan-view form of Clovis points can contribute to differences in functionality. Additional high internal validity analyses designed to investigate this observation are currently underway.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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