Modern thermoplastic (hot glue) versus organic-based adhesives and haft bond failure rate in experimental prehistoric ballistics

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Abstract:

The prehistoric production of composite technologies throughout human evolution was facilitated greatly by the use of adhesives. One such technology was projectile weaponry, which used adhesive to attach a stone point to a wooden shaft. Prehistoric projectile weaponry is often studied via experimental archaeology, which recreates ancient technologies to understand their manufacture and function. Here, we explore whether a modern thermoplastic adhesive can serve as a suitable replacement for two organic adhesives that would have been used by past peoples – pine resin and hide glue – in modern experimental tests of prehistoric weaponry. We conducted a ballistics experiment and shot groups of stone-tipped arrows, each group hafted with one of the three adhesives, and assessed the haft bond failure rate. The modern thermoplastic adhesive was similar to that of the pine resin and significantly failed less often than the hide glue. We conclude that in some cases modern thermoplastic adhesive can be substituted for organic-based adhesives in experimental archaeology. Our results also show that hafting bond failure rate was significantly different between the pine resin and the hide glue, suggesting that prehistoric hunter-gatherers faced costs or benefits in selecting adhesives for hafting.

Keywords:

Experimental archaeology; prehistoric weaponry; hafting; modern thermoplastic; pine resin; hide glue; ballistics

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1. Introduction

The advent of composite technology, specifically the attachment – hafting – of stone tools or components to handles or shafts, was an important milestone in hominin technological evolution and organization (Barham 2013; Blinkhorn 2019). By way of hafted tools, humans opened a realm of interchangeable technologies that continue to have ripple effects for our modern component-based technologies. Howard (1978) illustrates a modern example: Eli Whitney's interchangeable parts mode of manufacture that revolutionized 19th-Century gun production in America. Muskets manufactured with interchangeable parts allowed relatively unskilled workers to produce large numbers of weapons quickly and at lower cost, and made repair and replacement of parts infinitely easier. Hafting of interchangeable parts also changed the course of stone tool technology opening up possibilities for component-based technologies. Archaeologists, such as Lombard and Haidle (2012), have argued that component-based technologies mark prehistoric humans' ability to think through cognitively more complex thought and action sequences.

Hafted, component-based, technologies have several practical benefits. In the case of tools such as axe- or adze-heads, knife blades, or engravers, Barham (2013) notes that the added length would have provided by a bone, antler, ivory or wood handle enhanced the user's leverage (and thus force), stroke length, and control. For example, when hafted, a lithic axe-head can be used more effectively due to the potential energy generated by the longer arc of the user's swing: each swing cutting deeper and removing more material per strike, than if the flaked stone specimen were wielded by hand. Barham (2013) also suggests that hafting also allows users to wield tools in a safer manner. With the working lithic component placed at the end of a handle away from the user's fingers, hafting minimizes potential exposure to laceration, injury, and shock. In a prehistoric context, a smashed or cut finger, once infected, could mean sepsis or death. Like with all technological systems, hafting accrues process-dependent costs. For example, hafts need to be sourced, shaped, and prepared and these processes cost more in time and energy than making stone tool inserts. With respect to weaponry, our focus in this present study, the hafting of lithic spear-, dart-, or arrow-tips to shafts increased projectile haft integrity upon penetration (Bebber et al. 2017; Engelbrecht 2015; Waguespack et al. 2009).

Some composite tool technology would have been facilitated by the use of adhesives, which are substances used for binding objects or materials together. Indeed, Blinkhorn (2019) notes that one of the most secure forms of evidence for composite hafted technology (besides finding hafted tools) is through the recovery of adhesives on stone tools. Adhesives are present throughout the Paleolithic and post-Paleolithic archaeological records around the world, and they are comprised of a variety of substances (e.g. Aveling and Heron 1998; Blinkhorn 2019; Boeda et al. 1996, 2002, 2008; Carciumaru et al. 2006; Charrié-Dahaut et al. 2013; Cnuts et al. 2018; Connan 1999; Gibson et al. 2004; Helwig et al. 2008, 2014; Kozowyk et al. 2017; Lombard 2007; Mazza et al. 2006; Miller 2014; Monnier et al. 2013; Niekus et al. 2019; Pomstra and Meijer 2010; Regert 2004; Rots et al. 2011; Schenk and Groom 2016; Schmidt et al. 2019; Sheldrick et al. 1997; Stacey et al. 1998; Wadley et al. 2009; Wadley 2010; Yaroshevich et al. 2013). While the cognitive and behavioral significance adhesive production is debated (Grunberg 2002; Koller et al. 2001; Kozowyk et al. 2017; Roebroeks and Sorressi 2016; Schmidt et al. 2019; Sykes 2015), prehistoric toolmakers selected specific adhesive recipes (Kozowyk and Poulis 2019) and these are likely to have fundamentally changed how hominins made and used tools.

In experimental archaeology – archaeology's sub-discipline charged with recreating and reverse engineering ancient technologies to understand their manufacture and function – many researchers' focus on the making of prehistoric adhesives (see references in previous paragraph). This paper asks a different question, one more relevant to the function and use of adhesives as well as the materials, methods, and practice of experimental archaeology. In experimental prehistoric ballistics testing, does a modern thermoplastic adhesive – i.e., hot glue – function similarly to organic-based adhesives likely used in past? Following Lowe et al. (2019), this question is important for two reasons. First, acquiring or producing replica organic-based adhesives in the quantities necessary for statistical validity in experimental ballistics testing may be costly in time. Modern thermoplastics, however, are readily available. Second, with respect to experimental replication, two different laboratories may attempt to produce the same organic-based adhesive, but minor variations in temperature, ingredients, or procedures will inevitably result in two very different products (Wadley et al. 2009; Kozowyk et al. 2016). Using a standard modern thermoplastic would ameliorate or eliminate this problem. In sum, modern thermoplastic adhesives are inexpensive, available in bulk, replicable, and are fully homogenous in their chemical composition and physical structure.

While there are clear advantages in the use of modern thermoplastic adhesives for hafting stone projectile tips, these advantages would be amplified if modern thermoplastic adhesives behaved similarly to organic-based adhesives potentially used in the past. If a modern thermoplastic adhesive behaves similarly to an organic-based adhesive, then there is less sacrifice in ballistics experiments' external experimental validity, i.e. whether the experiment tracks actual prehistoric processes (e.g. Clarkson et al. 2015; Eren and Lycett 2013; Eren et al. 2016; Mesoudi 2011; Pettigrew et al. 2015; Roe and Just 2009). Ideally, the body (or build-up), plasticity, bond strength, and workability of a modern thermoplastic adhesive should be comparable to one or more of the following components of organic-based adhesives: bitumens, tree resin glues, or protein-glues (insect lac and hide glue).

There are a wide variety of modern adhesives that could be used for hafting that may or may not compare to prehistoric organic-based adhesives. Modern acrylic and epoxy, for example, should eventually be compared to organic-based adhesives. Our goal in this paper, as mentioned above, is to compare a modern, polymeric thermoplastic adhesive (hot melt glue), specifically Ferr-L-Tite™, produced by Bohning®, an archery supply manufacturer with two organic-based adhesives, pine resin and hide glue. The two adhesives were compared in a controlled ballistics experiment using replica weapon sets comprising stone tools and wooden hafts with the same dimensions. We hypothesized that if Ferr-L-Tite is a good proxy for one, or both, of the organic-based adhesives, then the stone projectile tips should dislodge from the fired arrows at the same rate, i.e. have similar bond-failure frequencies.

2. Materials and methods

2.1 Flaked stone projectile tips

M.W. flintknapped 30 triangular stone projectile tips from Keokuk chert using percussion and pressure flaking (**FIGURE 1**). The points were separated into three groups of 10, each group subsequently hafted using a different adhesive (described below). In order comply with modern "open access" standards and to help facilitate future experimental replication of our results, the morphometrics of each stone projectile tip are presented in **TABLE 1**. There were no significant differences in terms of each projectile tip group's length, width, basal width, or thickness (**TABLE 2**), given our Bonferroni-corrected alpha level of 0.0042 (*p*-values less than 0.0042 would be considered a statistically significant difference, see column 5 in Table 2).

2.2 Adhesives

We compared three hafting adhesives in this study. The first adhesive was Ferr-L-Tite™, a thermoplastic adhesive designed to mount threaded ferrules into the ends of modern carbon fiber or aluminum arrow shafts. The second adhesive was pine resin glue, based on

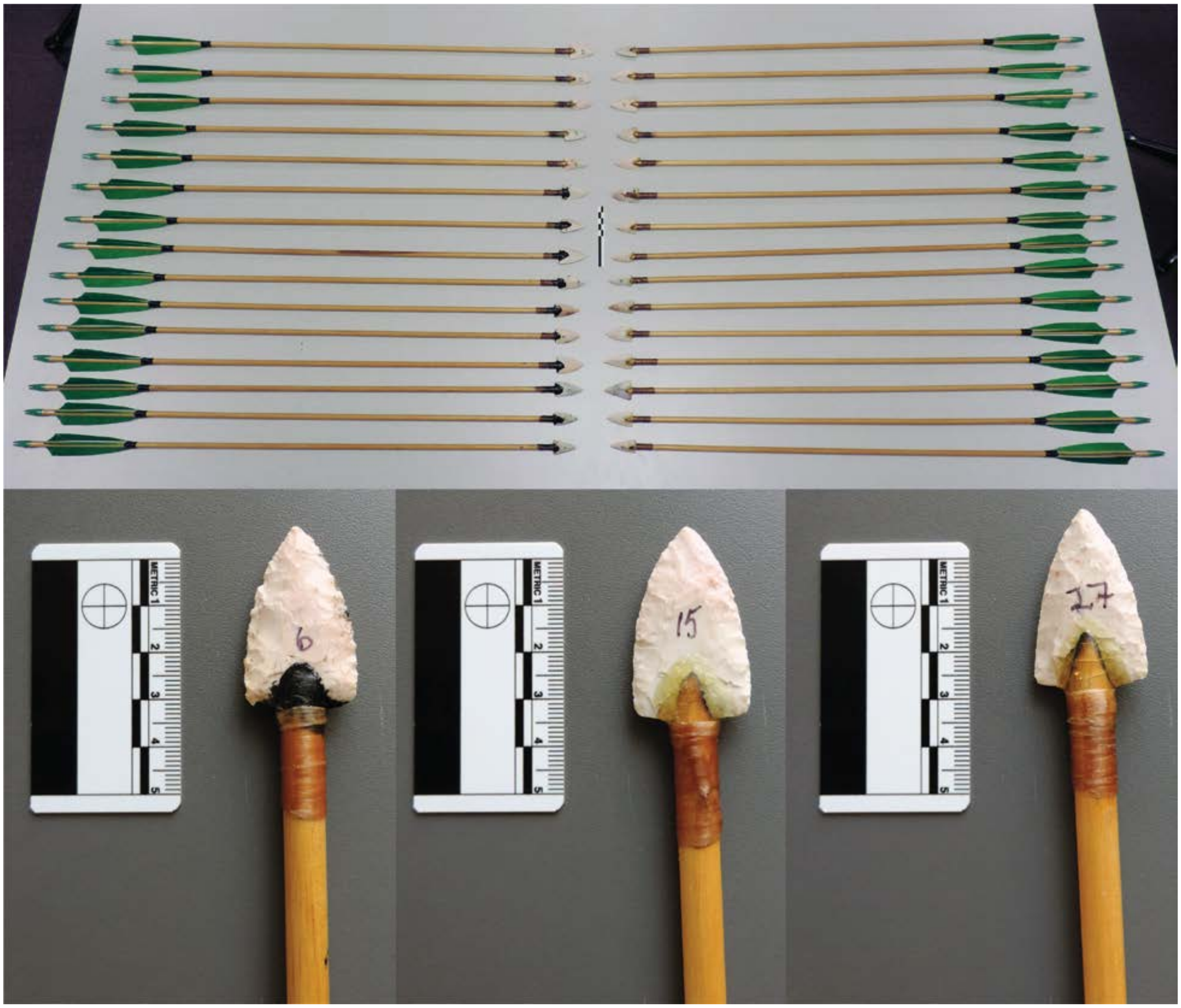

Figure 1. Examples of the finished projectiles (top) hafted with pine resin (bottom left), modern thermoplastic (bottom center), and hide glue (bottom right).

Table 1. Morphometric data of stone projectile points.

Adhesive group	Specimen	Point length (mm)	Point width (mm)	Point basal width (mm)	Point thickness (mm)	Point mass (g)
Pine resin	1	41.5	19.7	25.2	5.5	10.8
	2	36.4	21.0	25.4	5.1	10.2
	3	42.8	22.1	27.6	5.5	12.2
	4	41.2	22.0	22.8	6.3	14.2
	5	37.4	19.4	23.2	6.9	10.3
	6	36.8	22.0	23.1	8.1	11.2
	7	40.4	23.2	26.0	6.6	15.0
	8	41.0	19.3	23.4	7.2	12.3
	9	35.8	19.4	22.8	6.5	9.6
	10	33.4	17.1	22.0	5.6	9.8
	Mean	38.7	20.5	24.2	6.3	11.5
Modern thermoplastic	1	39.9	22.3	30.7	7.5	12.2
	2	42.3	23.6	27.2	6.2	14.8
	3	43.9	20.2	26.7	6.0	12.7
	4	37.4	21.5	24.2	6.7	12.3
	5	39.0	22.1	23.8	6.4	10.3
	6	39.0	19.8	23.8	6.9	10.4
	7	35.6	18.3	21.4	6.8	10.4
	8	36.8	18.0	23.4	5.6	8.7
	9	30.6	18.0	24.9	5.9	5.0
	10	33.4	15.8	18.9	7.3	10.6
	Mean	37.8	20.0	24.5	6.5	10.7
Hide glue	1	45.6	20.2	28.1	5.4	11.9
	2	40.7	24.4	27.3	7.8	8.6
	3	40.4	21.3	26.1	7.2	5.6
	4	41.0	21.0	26.6	4.3	8.4
	5	38.5	21.4	23.8	7.6	10.6
	6	39.9	17.3	22.2	8.3	8.5
	7	36.2	19.5	23.6	6.7	12.2
	8	34.1	20.2	26.8	7.2	10.1
	9	36.2	18.8	19.9	5.0	7.4
	10	33.6	18.0	20.0	5.1	10.4
	Mean	38.6	20.2	24.5	6.4	9.3

Table 2. Statistical comparisons of the adhesive projectile groups' morphometric variables, velocity, and penetration were conducted with an independent samples Kruskal-Wallis Test with Bonferroni corrected alpha-level (p = 0.05/12 = 0.0042).

Variable	Total N	Test Statistic	Degrees of Freedom	Asymptotic Sig. (2-sided)
Point length	30	0.379	2	0.827
Point width	30	0.210	2	0.900
Point basal width	30	0.560	2	0.756
Point thickness	30	0.350	2	0.839
Projectile mass	30	4.682	2	0.096
Binding length	30	1.644	2	0.440
Binding width	30	1.281	2	0.527
Resin length	60	0.489	2	0.783
Resin width	60	8.685	2	0.013
Point and resin basal thickness	30	5.031	2	0.081
Velocity	130	0.940	2	0.625
Penetration	220	40.513	2	<0.001

'Cutler's Resin', an organic-based adhesive derived from coniferous trees, specifically from the *pinaceae* family, with emulsifiers and body additives to enhance workability. This organic-based adhesive is commonly used in archaeological experiments (i.e. Kozowyk et al. 2016) and shows adhesion impact performance is equal, if not slightly better, than other traditional organic-based adhesives. The third adhesive was hide glue (Bleicher et al. 2015; Lowrey 1999; Petillon et al. 2011), an organic-based adhesive derived from animal collagen, here specifically from Eastern cottontail rabbit, *Leporidae Lagomorpha*.

All three of the tested adhesives required some secondary efforts to prepare. Ferr-L-Tite™ melts at around 155˚C (although the product description website states it melts at 176.7˚C). As the adhesive melts it becomes viscous, allowing for transfer to the hafting site. As with any heat activated adhesive, all mating surfaces must be warmed; not to the melting point of the adhesive, but warm enough to allow for adequate "wetting" of the joining surfaces to assure a uniform and integral bond. The Ferr-L-Tite was heated for application in two ways. First, for the bulk of the hafting (filling the haft pockets and fixing the points), the adhesive was heated in a 200ml pyrex lab beaker on an electric hot plate. After application with wooden craft sticks, the adhesive was reheated for fine tuning and binding with a can of Sterno™ gel. The canned gel was ideal for this purpose, providing a concentrated, yet low and controllable heat. The canned gel was also used to heat the haft pocket on the shaft and the basal end of each point. The adhesive cooled relatively fast in thinner applications; thicker applications required longer setting times. While cooling, the modern thermoplastic adhesive was workable with the fingertips as long as nitrile gloves were worn. After thoroughly cooling, the adhesive provided a homogenous, partially pliable, and a strong bond between the stone insert and wooden haft.

The pine resin was a composite organic-based adhesive. We used a formula referred to by craftspeople and toolmakers as ‘Cutler’s Resin’. The pine resin glue has a melting point of 120˚C[EM1], at which point its viscosity allows for transfer. Similarly, to the modern thermoplastic adhesive, all mating surfaces need to be warmed for thorough wetting with the pine resin. We heated the resin adhesive in a 200ml pyrex beaker with careful attention paid to the intensity of the heat during the mixing of the components. If the mixture overheated, the turpins in the resin would flash off and the resin would become too brittle. To save time and facilitate application, several resin ‘lollipops’ were constructed by accumulating a mass of resin on the ends of several craft sticks. The resin lollipops were then reheated over the canned gel and then applied to the warmed haft pocket and basal end of the stone points for projectile assembly. As the resin glue cooled, it became less viscous, and was workable for several seconds. The components of the pine resin resin glue included five parts of pine resin from Thunderbird Atlal™, one-part charcoal, one part wood dust (Osage Orange, *Malclura pomifera*), and one part beeswax (5:1:1:1) [EM2](e.g. Fletcher et al. 2018; but see Croft et al. 2018). The charcoal is used as an emulsifier, the wood dust builds aggregate and body (elsewhere referred to as a ‘loading’ agent, Gardner 2001) while the beeswax adds pliability and flexibility. The overall body-characteristic of the resulting adhesive was relatively homogenous, partially flexible, and provided an strong bond between the stone and wood projectile components.

Thunderbird Atlatl™ provided the granules for the hide adhesive. The dry granules came in four-ounce (113.4 g) packages. Hide glue is derived from animal collagen, made by boiling down animal skin and connective tissue. The glue for the final sample group was prepared by combining the hide glue granules and tap water in equal parts by volume. The granules and water were heated in a double boiler under medium heat with an electric hotplate. The glue was ready for application when the granules were fully dissolved. Suitable viscosity is achieved around 100˚C. We applied this adhesive with a craft stick; wetting the haft pocket along with the basal end of the points. It is important to point out that the hide adhesive proved more difficult to work with than the pine resin adhesive. Specifically, as the hide adhesive cooled, it became slippery, gelatinous, and sticky. The resulting adhesive is near impossible to tool or sculpt and it resembled a “jiggly” mass. However, the adhesive lost much of its body to evaporation (with 50% water volume) resulting in a uniform and hard substance.[EM3]

2.3 Hafting

M.W. hafted each group of 10 flaked stone tips with one of the three adhesives to an 8mm prefletched shafting made from Port Orford cedar **(FIGURE 1)**. We selected Port Orford cedar because it is widely used a revered by archery competitors and enthusiasts and easy to obtain. For the sake of expediency, prefletched shafts were procured from TTAD™. To accommodate the compression exerted by a 45lb (20.41 kg) recurve bow, the 76.2 cm x 8 mm shafting needed a spine index of at least .50’’-.55’’.

We used the same basic procedure to haft each of the stone flakes. Each shaft was tapered to accommodate the stone projectile point’s basal thickness. A pocket was then rough-cut into the shaft using a carpenter's coping saw followed by fine-tuning and pre-fitting of the haft with a sharp blade and files. The pocket and leading end of the shaft were then hardened with heat from the canned Sterno™ gel. We then warmed the basal end of a stone point and the adhesive while heating the adhesive to its melting point. After fully wetting the mating surfaces (the socket and the basal end of the point), the points were inserted, centered, and then inserted, centered, and balanced by hand. The modern thermoplastic adhesive and the Cutler's resin were malleable so that as the adhesives cooled, M.W. was able to sculpt and form the haft site. This enabled him to fill voids and complete a uniform convexity on each of the projectile's faces. The hide adhesive was not as easily manipulated. It congealed and became clumpy during cooling and as M.W. tried to sculpt it. The hide adhesive took upwards of four hours to dry while the modern thermoplastic and pine resin took minutes to set.

After the respective glue was set, binding was applied. For binding the haft sites, we chose an artificial sinew. This product is a multistrand polyester filament, coated in beeswax and rated at 70lb (31.75 kg) test strength to prevent shafts splitting upon impact.

In order comply with modern "open access" standards and to help facilitate future experimental replication of our results **TABLE 3** presents the morphometrics of each finished, hafted projectile. There were no significant differences in terms of each group's average projectile mass, binding length, binding width, resin length, resin width, or point and resin basal thickness (**TABLE 2**).

Table 3. Morphometric data of projectiles and hafting.

Adhesive group	Specimen	Projectile mass (g)	Binding length (mm)	Binding width (mm)	Resin length 1 (mm)	Resin length 2 (mm)	Resin width 1 (mm)	Resin width 2 (mm)	Point and resin basal thickness (mm)
Pine resin	1	36.80	29.82	9.66	14.25	12.39	14.70	12.90	8.76
	2	36.20	22.50	9.99	16.97	16.17	14.21	14.40	8.95
	3	38.20	23.36	9.81	16.63	14.20	14.11	11.76	8.99
	4	40.20	25.83	9.94	12.54	10.68	16.28	17.72	9.17
	5	36.30	27.31	9.54	13.11	11.50	14.17	15.65	8.91
	6	37.20	21.56	10.12	8.62	8.46	11.47	11.12	9.24
	7	41.00	24.03	9.93	11.55	12.73	11.62	13.04	8.90
	8	38.30	20.05	10.17	13.68	10.85	15.18	18.62	9.56
	9	35.60	20.43	10.43	13.22	15.63	11.05	13.39	8.47
	10	35.80	21.37	9.69	10.13	9.33	11.84	12.36	8.20
	Mean	37.56	23.63	9.93	13.07	12.19	13.46	14.10	8.92
Modern thermoplastic	1	38.20	33.05	9.93	11.21	10.08	13.24	14.45	8.86
	2	40.80	27.32	9.91	15.30	14.56	12.33	13.88	10.00
	3	38.70	36.14	9.69	14.59	14.52	14.44	14.96	9.06
	4	38.30	25.79	9.72	17.89	14.65	11.67	12.36	8.83
	5	36.30	24.18	9.80	12.87	12.71	14.68	14.99	9.56
	6	36.40	26.10	9.40	10.14	10.13	13.44	12.75	8.75
	7	36.40	24.08	9.96	8.33	11.60	9.50	10.63	8.73
	8	34.70	23.51	9.98	13.04	14.24	11.96	14.26	9.27
	9	31.00	21.50	9.72	11.95	9.96	12.20	8.65	8.67
	10	36.60	18.82	10.04	7.54	7.60	11.12	10.71	9.14
	Mean	36.74	26.05	9.82	12.29	12.01	12.46	12.76	9.09
Hide glue	1	37.90	31.20	9.91	15.54	13.78	12.32	11.95	8.81
	2	34.60	26.86	9.73	9.98	12.43	15.50	11.60	8.95
	3	31.60	24.31	10.12	10.45	11.88	14.47	11.99	8.69
	4	34.40	33.04	9.67	15.32	14.65	12.06	10.07	8.52
	5	36.60	24.78	9.16	10.51	10.80	11.68	11.89	8.42
	6	34.50	25.37	9.90	11.27	10.65	10.46	10.57	8.91
	7	38.20	20.19	10.31	14.60	13.34	11.66	12.13	9.17
	8	36.10	21.54	9.16	9.62	10.01	11.71	9.65	8.59
	9	33.40	22.86	9.78	11.54	13.40	10.41	12.22	8.47
	10	36.40	21.23	9.88	12.23	10.74	10.82	13.19	8.10
	Mean	35.37	25.14	9.76	12.11	12.17	12.11	11.53	8.66

2.4 Experimental procedure

The experiment was conducted in a heated commercial bay, normally used for carpentry and cabinet making. A space was cleared for the installation of an adequate archery backstop and target. The target medium was comprised of two layers of two-inch-thick (5.08 cm), medium-density construction foam-board, called Formular™ by Owens Corning (**FIGURE 2**). While foam-board is not a proxy for meat or bone, it provided a consistent impact and penetration resistance to "jostle" each projectile thereby testing each adhesive's bond strength (**FIGURE 3**). We used a sheet of 8oz vinyl Naugahyde® pinned to the impact side of the target to simulate an animal's hide. The square target measured 61 cm by 61 cm and was 10.2 cm thick. We mounted the target to a wooden, L-shaped bracket with 12-inch (30.48 cm) bar clamps to move to target as needed. Shifting the target efficiently allowed the archer (M.W.) to place his shots into 'fresh' target medium each time, facilitating maximum potential for similar impact conditions and maintaining relative control over penetration resistance (i.e. so every shot would encounter the same amount of resistance). The space was 3 m, the front face of the bow to the face of the target. All projectiles were extracted from the back of the target so as to not subject the haft sites to additional bond stress, with the exception of projectile #30 which was mistakenly removed back through its entrance hole, dislodging the point prematurely. This specimen was removed from the analysis. Each individual projectile was shot up to 10 times or until the haft-bond failed.

We used a traditional 45lb (20.41 kg), takedown recurve bow made by Fleetwood Archery™ (**FIGURE 2**). M.W. is a bow-hunter and was able to keep his shot accuracy (grouping at an 8cm radius) and draw length consistent at 72.4 cm. We chose to shoot each arrow by hand with a recurve bow rather than with a "bow tuning machine" (e.g. Bebber and Eren 2020) to help ensure each point was "jostled". Our concern with the use of a bow tuning machine was that arrows would fly so straight and true that the adhesives would not experience adequate resistance between shots and thus their thresholds would not be tested. Shooting by hand allowed slight, natural variations that contributed to our assessment of our intended dependent variable: haft bond failure rate (Eren et al. 2016; Lycett and Eren 2013).

We measured velocity throughout the experiment to ensure that each projectile similarly impacted the foam board using a Gamma Master Model Shooting Chronograph (**FIGURE 2)** (Bebber and Eren 2020; Bebber et al. 2020; Mika et al. 2020; Werner et al. 2019). The Chronograph is sensitive and prone to error readings; we thus recorded 55 pine resin velocity readings (mean velocity = 48.34 m/s), 51 modern thermoplastic velocity readings (mean velocity = 47.39 m/s), and 24 hide glue velocity readings (mean velocity = 48.29 m/s). There were no significant differences in projectile velocity among the groups (**TABLE 2**).

We also measured each projectile's penetration depth into the foam board to assess whether the interaction was similar among each adhesive group and the foam board. Given bond failure rates (see results below), we recorded 86 pine resin penetration, 97 modern thermoplastic penetration measurements, and 37 hide glue penetration measurements.

3. Results

TABLE 4 presents the bond failure rates for the three adhesive groups. On average, a flaked stone tip hafted with pine resin will last 8.6 out of 10 shots before bond failure; hafted with modern thermoplastic will last 9.7 shots; and hafted with hide glue will last 3.7 shots. These differences are significant (Kruskal-Wallis, Total N = 29, Test Statistic = 11.517, df = 2, Asymptotic Significance [2-sided] = 0.003). Post-hoc pairwise comparisons indicate that there is no difference in bond-failure rate between the pine resin and modern thermoplastic (Test Statistic = -1.800, Std. Test Statistic = 0.576, Adjusted Significance = 1.000). There are differences in bond failure rate between the hide glue and modern thermoplastic (Test Statistic = 10.567, Std. Test Statistic =

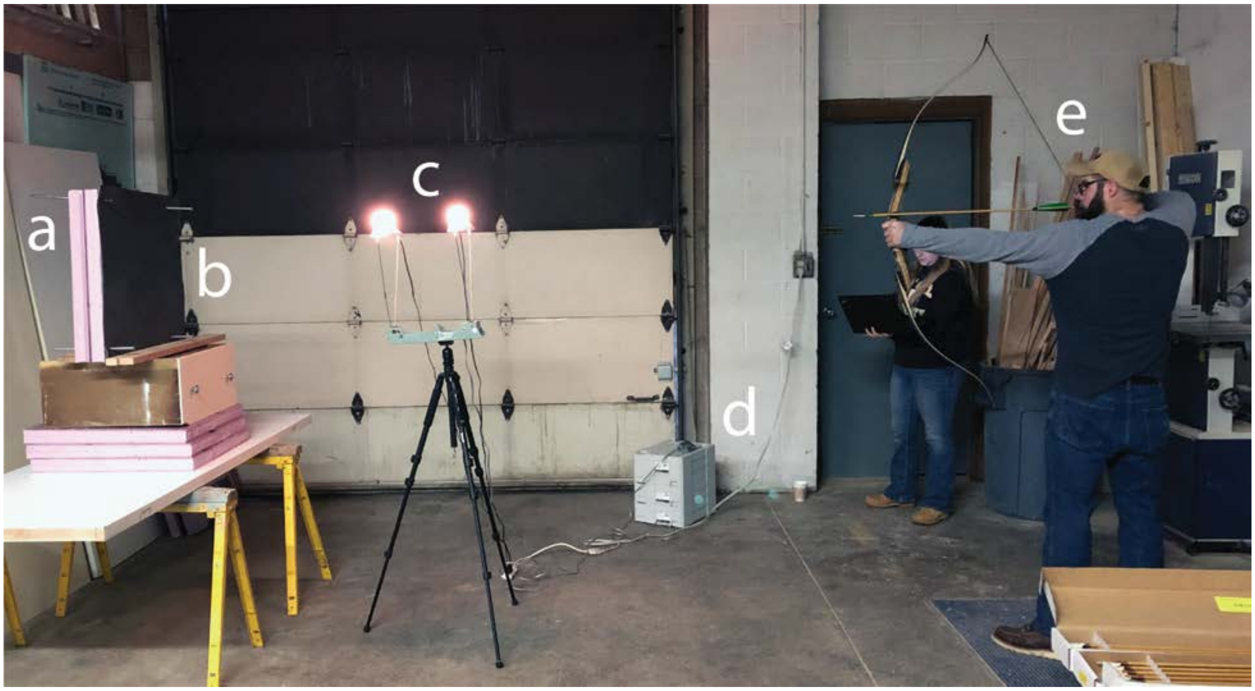

Figure 2. The experimental set up included two layers of two-inch-thick (5.08 cm), medium-density construction foam-board (a) covered by a sheet of 8oz vinyl Naugahyde (b). Arrows were shot through a chronometer (c) so velocity could be recorded (d). M.W. used a recurve bow to shoot the arrows approximately three meters from the target (e).

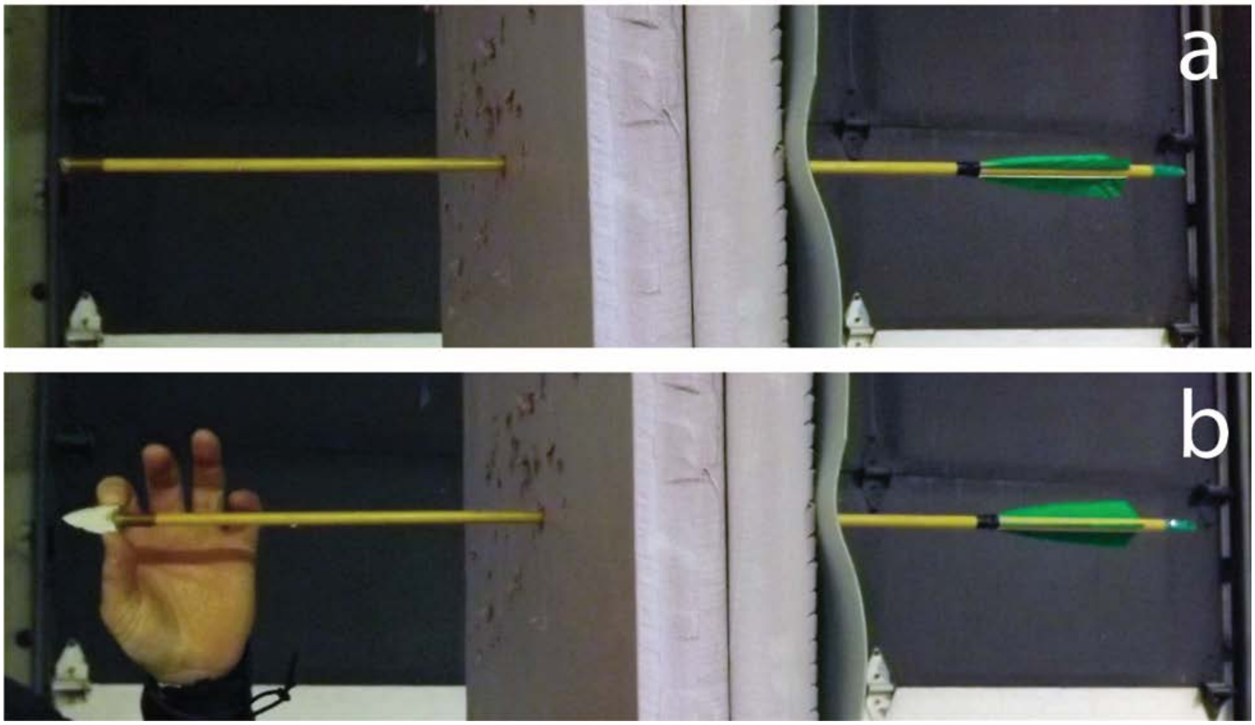

Figure 3. An example of an arrow penetrating the foam board, in this case the stone point haft-bond failed (top); the stone point refit back onto the arrow shaft (bottom).

Table 4. The number of shots out of ten each projectile withstood.

Projectile	Pine resin	Penetration depth at failure	Modern thermoplastic	Penetration depth at failure	Hide glue	Penetration depth at failure
1	10	n/a	10	n/a	1	20.1 cm
2	10	n/a	10	n/a	2	15.5 cm
3	10	n/a	10	n/a	1	n/a
4	10	n/a	10	n/a	2	19.9 cm
5	10	n/a	10	n/a	10	n/a
6	5	24.8 cm	10	n/a	1	14.5 cm
7	10	n/a	7	31.7 cm	9	14.1 cm
8	10	n/a	10	n/a	10	n/a
9	10	n/a	10	n/a	1	15.9 cm
10	1	25.8 cm	10	n/a	Error	n/a
Mean	8.6		9.7		3.7	

3.196, Adjusted Significance = 0.004) and hide glue and pine resin (Test Statistic = 8.767, Std. Test Statistic = 2.562, Adjusted Significance = 0.024). All the associated effect sizes were large (modern thermoplastic vs. hide glue, r = 0.59; hide glue vs. pine resin, r = 0.49) (Field 2014).

Another way to assess the results is to examine the frequency of projectiles that lasted all 10 shots versus those that did not. We thus compared each adhesive group with a series of Fisher Exact Tests. These results mirror those of the previous paragraph: there is no difference in bond failure rate between modern thermoplastic and pine resin (Fisher Exact p = 0.100); but there are significant differences between modern thermoplastic and hide glue (Fisher Exact p = 0.005) and pine resin and hide glue (Fisher Exact p = 0.023).

With respect to projectile penetration, the pine resin projectiles on average penetrated the foam board 20.06 cm; the modern thermoplastic projectiles 24.14 cm; and the hide glue projectiles 19.50 cm. These means represent a significant difference (**TABLE 2**). Post-hoc pairwise comparisons showed no significant difference between the pine resin and hide glue (Test Statistic 2.865, Std Test Statistic 0.229, Adjusted Significance p=1.000) (**TABLE 2**). However, there were significant differences in penetration depth between the modern thermoplastic and the pine resin (Text Statistic -54.115, Std Test Statistic -5.740, Adjusted Significance p<0.001) and the modern thermoplastic and the hide glue (Test Statistic 56.980, Std Test Statistic 4.633, Adjusted Significance p<0.001). Following Field (2014:82, 227) we calculated the effect size for these differences, the result of which represented a medium effect for each difference (modern thermoplastic vs. pine resin, r = -0.39; modern thermoplastic vs. hide glue, r = 0.31.).

We predicted that the penetration depth was similar among the three adhesive groups. The significant differences in penetration depth between the modern thermoplastic and each of the two organic-based adhesives were thus unexpected. We expand on these differences in the discussion section below, since it is important consider them in light of the variable we intended to examine, hafting bond-failure rate.

4. Discussion

As experimental archaeology continues to mature as a discipline, the materials, methods, and procedures archaeologists use in experiments should be examined with increasing scrutiny. All of these experimental factors can potentially influence results (cf. Eren et al., 2016). Improving our understanding of how different materials behave is also an important aspect of a maturing archaeological science. Moreover, understanding how certain modern materials or practices compare to past analogues is important for accurately interpreting modern experiments' external validity relative to past activities.

Here, we compared a modern thermoplastic adhesive to two "traditional" organic-based adhesives (hide glue and pine resin) widely used in archaeological experiments (e.g. Romanus et al. 2009; Duce et al. 2015; Kozowyk et al. 2016). Firing groups of 10 stone points hafted with each of the three adhesives under controlled conditions yielded unequivocal results with respect to haft bond failure rate. The modern thermoplastic adhesive was similar to that of the pine resin and significantly stronger than the hide glue. Thus, we can conclude that modern thermoplastic adhesive can be substituted for some organic-based adhesives. However, these results have varying levels of relevance depending on the experimental design and research question. For experiments dealing with prehistoric weaponry, modern thermoplastic adhesives may serve as good adhesive substitutes; but for experiments involving specific geo-temporal contexts, the use of modern thermoplastic adhesives may be inappropriate if adhesives akin to hide glue were used.

Although not the primary focus or result of the experiment, it is important to note that comparisons of the hafting bond failure rate was significantly different between the pine resin and the hide glue. This result suggests that there are important costs or benefits prehistoric foragers may have faced if they were in a position to choose one adhesive over another. Pine resin, the significantly stronger of the two, would be advantageous to foragers wishing to keep their projectiles intact, reducing the probability of losing their stone tips – even damaged ones – in a carcass or in underbrush. Likewise, poor hafting bond failure rates should also not automatically be viewed as a "negative". In the same way a broken stone projectile tip may increase damage to prey or an enemy (Bebber et al. 2017; Engelbrecht 2015; Ellis 1997), a stone tip that becomes detached from its shaft may produce additional internal damage to prey or an enemy, while allowing the shaft to be retrieved. One must also acknowledge, however, that not everyone in the past had ready access to the same resources. Geography may eliminate any consideration of costs and benefits in the prehistoric toolkit, if, for example, pine trees are not present.

That said, unlike clay (Key et al. 2018), foam has not been shown to be a reliable proxy for meat, bone, or anything prehistoric foragers would have struck. The foam we use here provided a consistent impact resistance for the testing of the *relative* hafting bond failure rate – but not necessarily *realistic* bond failure rate. Thus, future research should re-test these results on clay, meat, or an actual animal carcass. Future research should also compare foam to these latter three mediums.

To our knowledge, there has never been an archaeological experiment that investigated adhesives in the way we have here. As such, there is much to be done, and beyond looking at the foam, there are many other experimental variables and conditions that need to be explored and tested. For example, another avenue of future research involves hafting adhesive effects penetration. We noted in the materials and methods section that the arrows hafted with modern thermoplastic adhesive penetrated significantly farther into the foam target than did the arrows with the pine resin or hide glue. This result suggests that in terms of penetration, modern thermoplastic adhesive may be used for *relative* comparisons between projectiles, but not necessarily *realistic* ones. The reason for the difference in penetration between the modern thermoplastic adhesive versus the two traditional adhesives may have to do with drag. Post-firing, all the adhesives showed vertical striations from penetrating the foam, but the drag features in the pine resin and the hide glue examples appeared deeper (**FIGURE 4**). This result suggests that the foam target was "grabbing" these latter projectiles and potentially slowing them down, decreasing penetration relative to the projectiles hafted with modern thermoplastic adhesives. Another possibility is that the high haft bond failure rate of the hide glue group was decreasing its overall penetration (**TABLE 4**). This explanation, however, does not explain the difference in penetration between the modern thermoplastic and pine resin groups, which possessed statistically similar haft bond failure rates but significantly different penetration depths. Nor does haft bond failure rate explain the statistical similarity between the pine resin and hide glue penetration depths. Yet another possibility to explore are the coefficients of friction for each of the three adhesives.

Figure 4. Striations parallel to the direction of shooting were present in the modern thermoplastic (left), pine resin (center), and hide glue (right) adhesives.

Increasing the number of shots per projectile specimen might be a profitable avenue of future experiments. Here, we limited the number of shots per arrow to 10 because the ethnographic literature suggests that 10 shots is actually quite a large number. Speaking directly to this issue, Ellis (1997) notes that stone points frequently break up in the wound, requiring constant tip replacement and re-hafting. Beyond this, and further precluding a high number of shots per projectile specimen, Ellis (1997:57) notes that ethnographic evidence suggests that stone tips "would break or at least be damaged with every missed shot". The brittleness of stone tips means that success or failure likely results in their damage and replacement. So, while it is entirely possible that increasing the number of shots per specimen may potentially reveal a difference in haft bond failure rates between the modern thermoplastic and pine resin adhesives, it would remain an open question as to what 20, 30, or 40 shots per specimen would mean in terms of prehistoric or ethnographic forager reality if these larger shot numbers were not possible to achieve. And even if a *significant* difference between the modern thermoplastic and pine resin haft bond failure rates was revealed by increasing the experimental sample size of shots per arrow, an analysis of effect size would have to be performed to understand whether that difference was a *practice* one.

Finally, some other areas of future research may include comparative studies concerning the material behavior of other modern adhesives such as epoxy liquids, pastes, and putties. There are several distributors that produce these durable and easily obtainable products at relatively low cost. Some of this research might include high degrees of internal validity, focusing on the material bond dynamics, physically independent of other prehistoric composite tool components (shafts, propulsion modality, and even flaked stone tools). As suggested by Kozowyk et al. (2016), lap shear testing is effective at parsing out minute behavioral differences in adhesives. With these methods, they were able to evaluate the performance of several different composite adhesive formulas.

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References

Aveling E, Heron C. Identification of birch bark tar at the Mesolithic site of Star Carr. Ancient Biomolecules 1998;2(1):69-80.

Barham L. From Hand to Handle: The First Industrial Revolution. Oxford University Press; 2013.

Bebber MR, Eren MI. Toward a functional understanding of the North American Old Copper Culture "technomic devolution". Journal of Archaeological Science 2018;98:34-44.

Bebber MR, Lycett SJ, Eren MI. Developing a stable point: evaluating the temporal and geographic consistency of Late Prehistoric unnotched triangular point functional design in Midwestern North America. Journal of Anthropological Archaeology 2017;47:72-82.

Bebber MR, Wilson M, Kramer A, Meindl RS, Buchanan B, Eren MI. The non-invention of the ceramic arrowhead in world archaeology. Journal of Archaeological Science: Reports 2020;31:102283.

Beck CW. Comments on a supposed Clovis "mastic". Journal of Archaeological Science 1996;23:459-60.

Bleicher N, Kelstrup C, Olsen JV, Cappellini E. Molecular evidence of use of hide glue in 4th millennium BC Europe. Journal of Archaeological Science. 2015;63:65-71.

Blinkhorn J. Examining the origins of hafting in South Asia. Journal of Paleolithic Archaeology 2019;2(4):466-81.

Boëda E, Connan J, Dessort D, Muhesen S, Mercier N, Valladas H, Tisnérat N. Bitumen as a hafting material on Middle Palaeolithic artefacts. Nature 1996;380(6572):336-8.

Boëda E, Connan J, Muhesen S. Bitumen as hafting material on Middle Paleolithic artifacts from the El Kowm Basin, Syria. In Akazawa T, Aoki K, Bar-Yosef O (editors), Neandertals and Modern Humans in Western Asia 2002 (pp. 181-204). Springer, Boston, MA.

Boëda É, Bonilauri S, Connan J, Jarvie D, Mercier N, Tobey M, Valladas H, Sakhel HA. New evidence for significant use of bitumen in Middle Palaeolithic technical systems at Umm el Tlel (Syria) around 70,000 BP. Paléorient 2008:67-83.

Cârciumaru M, Ion RM, Niţu EC, Ştefãnescu R. New evidence of adhesive as hafting material on Middle and Upper Palaeolithic artefacts from Gura Cheii-Râşnov Cave (Romania). Journal of Archaeological Science;39(7):1942-50.

Charrié-Duhaut A, Porraz G, Cartwright CR, Igreja M, Connan J, Poggenpoel C, Texier PJ. First molecular identification of a hafting adhesive in the late Howiesons Poort at Diepkloof Rock Shelter (Western Cape, South Africa). Journal of Archaeological Science 2013;40(9):3506-18.

Clarkson C, Haslam M, Harris C. When to retouch, haft, or discard? Modeling optimal use/maintenance schedules in lithic tool use. In Goodale N, Andrefsky W (editors), Lithic Technological Systems and Evolutionary theory 2015 (pp. 117-38). Cambridge, Cambridge University Press.

Cnuts D, Tomasso S, Rots V. The role of fire in the life of an adhesive. Journal of Archaeological Method and Theory 2018;25(3):839-62.

Connan J. Use and trade of bitumen in antiquity and prehistory: molecular archaeology reveals secrets of past civilizations. Philosophical Transactions of the Royal Society of London Series B: Biological Sciences 1999;354(1379):33-50.

Croft S, Chatzipanagis K, Kröger R, Milner N. Misleading residues on lithics from Star Carr: identification with Raman microspectroscopy. Journal of Archaeological Science: Reports 2018;19:430-8.

Duce C, Orsini S, Spepi A, Colombini MP, Tiné MR, Ribechini E. Thermal degradation chemistry of archaeological pine pitch containing beeswax as an additive. Journal of Analytical and Applied Pyrolysis 2015;111:254-64.

Ellis CJ. Factors influencing the use of stone projectile tips. In Knecht H (editor), Projectile Technology 1997 (pp. 37-74). Springer, Boston, MA.

Engelbrecht W. Interpreting broken arrow points. American Antiquity 2015;80(4):760-6.

Eren MI, Lycett SJ, Patten RJ, Buchanan B, Pargeter J, O'Brien MJ. Test, model, and method validation: the role of experimental stone artifact replication in hypothesis-driven archaeology. Ethnoarchaeology 2016;8(2):103-36.

Field A. Discovering Statistics Using IBM SPSS Statistics. 2014. Sage, Thousand Oaks.

Fletcher L, Milner N, Taylor M, Bamforth M, Croft S, Little A, Pomstra D, Robson HK, Knight B. The use of birch bark. In Milner N, Conneller C, Taylor B (editors), Star Carr 2018 (pp. 419-435). White Rose University Press.

Gardner D. Wood: Surface Properties and Adhesion. *Encyclopedia of Materials: Science and Technology* (2nd edition) 2001:9745-9748.

Gibson NE, Wadley L, Williamson BS. Microscopic residues as evidence of hafting on backed tools from the 60 000 to 68 000 year-old Howiesons Poort layers of Rose Cottage Cave, South Africa. Southern African Humanities 2004;16(1):1-1.

Grünberg JM. Middle Palaeolithic birch-bark pitch. Antiquity 2002;76(291):15-6.

Helwig K, Monahan V, Poulin J. The identification of hafting adhesive on a slotted antler point from a southwest Yukon ice patch. American Antiquity 2008;73(2):279-88.

Helwig K, Monahan V, Poulin J, Andrews TD. Ancient projectile weapons from ice patches in northwestern Canada: identification of resin and compound resin-ochre hafting adhesives. Journal of Archaeological Science 2014;41:655-65.

Howard R Interchangeable parts re-examined: The private sector of the American arms industry on the eve of the Civil War, Technology and Culture 1978;19:633-649.

Key A, Young J, Fisch MR, Chaney ME, Kramer A, Eren MI. Comparing the use of meat and clay during cutting and projectile research. Engineering Fracture Mechanics 2018;192:163-75.

Koller J, Baumer U, Mania D. High-tech in the Middle Palaeolithic: Neandertal-manufactured pitch identified. European Journal of Archaeology 2001;4(3):385-97.

Kozowyk PRB, Langejans GHJ, Poulis JA. Lap shear and impact testing of ochre and beeswax in experimental Middle Stone Age compound adhesives. PLoS ONE 2016;11(3):e0150436.

Kozowyk PRB, Poulis JA, Langejans GHJ. Laboratory strength testing of pine wood and birch bark adhesives: A first study of the material properties of pitch. Journal of Archaeological Science: Reports 2017;13:49-59.

Kozowyk, PRB, Poulis JA. A new experimental methodology for assessing adhesive properties shows that Neandertals used the most suitable material available. Journal of Human Evolution 2019;137:102664.

Lombard M. The gripping nature of ochre: the association of ochre with Howiesons Poort adhesives and Later Stone Age mastics from South Africa. Journal of Human Evolution. 2007;53(4):406-19.

Lombard M. Evidence of hunting and hafting during the Middle Stone Age at Sibidu Cave, KwaZulu-Natal, South Africa: a multianalytical approach. Journal of Human Evolution 2005;48(3):279-300.

Lombard M, Haidle M. Thinking a bow-and-arrow set: Cognitive implications of Middle Stone Age bow and stone-tipped arrow technology, Cambridge Archaeological Journal 2012;22:237-264.

Lombard M, Phillipson L. Indications of bow and stone-tipped arrow use 64 000 years ago in KwaZulu-Natal, South Africa. Antiquity 2010;84(325):635-48.

Lowe C, Kramer A, Wilson M, Meindl R, Spurlock L, Eren MI. Controlled ballistics tests of ground, percussion-flaked, and pressure-flaked projectile point impact durability: Implications for archaeological method and theory. Journal of Archaeological Science: Reports 2019;24:677-82.

Lowrey NS. An ethnoarchaeological inquiry into the functional relationship between projectile point and armor technologies of the Northwest Coast. North American Archaeologist. 1999;20(1):47-73.

Lycett SJ, Eren MI. Levallois lessons: the challenge of integrating mathematical models, quantitative experiments and the archaeological record. World Archaeology. 2013;45(4):519-38.

Mazza PPA, Martini F, Sala B, Magi M, Colombini MP, Giachi G, Landucci F, Lemorini C, Modugno F, Ribechini E. A new Palaeolithic discovery: tar-hafted stone tools in a European Mid-Pleistocene bone-bearing bed. Journal of Archaeological Science 2006;33(9):1310-8.

McBrearty S, Tryon C. From Acheulean to Middle Stone Age in the Kapthurin Formation, Kenya. In Hovers E, Kuhn S (editors), Transitions Before the Transition 2006 (pp. 257-277). Springer, Boston, MA.

Mesoudi A. Cultural Evolution. Chicago: University of Chicago Press; 2011.

Mika A, Flood K, Norris JD, Wilson M, Key A, Buchanan B, Redmond B, Pargeter J, Bebber MR, Eren MI. Miniaturization optimized weapon killing power during the social stress of late pre-contact North America (AD 600-1600). PLoS ONE 2020;15(3):e0230348.

Miller GL. Lithic microwear analysis as a means to infer production of perishable technology: a case from the Great Lakes. Journal of Archaeological Science 2014;49:292-301.

Monnier GF, Hauck TC, Feinberg JM, Luo B, Le Tensorer JM, Al Sakhel H. A multi-analytical methodology of lithic residue analysis applied to Paleolithic tools from Hummal, Syria. Journal of Archaeological Science 2013;40(10):3722-39.

Niekus M, Kozowyk PR, Langejans G, Ngan-Tillard D, van Keulen H, van der Plicht J, Cohen K, van Wingerden W, van Os B, Smit B, Amkreutz L, Johansen L, Verbaas A, Dusseldorp G/ Middle Paleolithic complex technology and a Neandertal tar-backed tool from the Dutch North Sea. Proceedings of the National Academy of Sciences USA 2019; 116(44):22081.

Pettigrew DB, Whittaker JC, Garnett J, Hashman P. How atlatl darts behave: beveled points and the relevance of controlled experiments. American Antiquity 2015;80(3):590-601.

Pétillon JM, Bignon O, Bodu P, Cattelain P, Debout G, Langlais M, Laroulandie V, Plisson H, Valentin B. Hard core and cutting edge: experimental manufacture and use of Magdalenian composite projectile tips. Journal of Archaeological Science 2011;38(6):1266-83.

Regert M. Investigating the history of prehistoric glues by gas chromatography–mass spectrometry. Journal of Separation Science 2004;27(3):244-54.

Roe BE, Just DR. Internal and external validity in economics research: Tradeoffs between experiments, field experiments, natural experiments, and field data. American Journal of Agricultural Economics 2009;91(5):1266-71.

Roebroeks W, Soressi M. Neandertals revised. Proceedings of the National Academy of Sciences. 2016;113(23):6372-9.

Romanus K, Baeten J, Poblome J, Accardo S, Degryse P, Jacobs P, De Vos D, Waelkens M. Wine and olive oil permeation in pitched and non-pitched ceramics: relation with results from archaeological amphorae from Sagalassos, Turkey. Journal of Archaeological Science 2009;36(3):900-9.

Rots V. Towards an understanding of hafting: the macro-and microscopic evidence. Antiquity 2003;77(298):805-15.

Rots V, Van Peer P, Vermeersch PM. Aspects of tool production, use, and hafting in Palaeolithic assemblages from Northeast Africa. Journal of Human Evolution 2011;60(5):637-64.

Schmidt P, Blessing M, Rageot M, Iovita R, Pfleging J, Nickel KG, Righetti L, Tennie C. Birch tar production does not prove Neanderthal behavioral complexity. Proceedings of the National Academy of Sciences 2019;116(36):17707-11.

Sheldrick C, Lowe JJ, Reynier MJ. Palaeolithic barbed point from Gransmoor, East Yorkshire, England. InProceedings of the Prehistoric Society 1997 (Vol. 63, pp. 359-370). Cambridge University Press.

Stacey RJ, Heron C, Sutton MQ. The chemistry, archaeology, and ethnography of a native American insect resin. Journal of California and Great Basin Anthropology 1998;20:53-71.

Stacey RJ, Cartwright CR, McEwan C. Chemical characterization of ancient mesoamerican 'copal' resins: preliminary results. Archaeometry 2006;48(2):323-40.

Takahashi C, Nelson D, Southon S. Radiocarbon and stable isotope analyses of archaeological bone consolidated with hide glue. Radiocarbon 2002;44:59-62.

Wadley L. Compound-adhesive manufacture as a behavioral proxy for complex cognition in the Middle Stone Age. Current Anthropology 2010;51(S1):S111-9.

Wadley L, Williamson B, Lombard M. Ochre in hafting in Middle Stone Age southern Africa: a practical role. Antiquity 2004;78(301):661-75.

Wadley L, Hodgskiss T, Grant M. Implications for complex cognition from the hafting of tools with compound adhesives in the Middle Stone Age, South Africa. Proceedings of the National Academy of Sciences 2009;106(24):9590-4.

Waguespack NM, Surovell TA, Denoyer A, Dallow A, Savage A, Hyneman J, Tapster D. Making a point: wood-versus stone-tipped projectiles. Antiquity 2009;83(321):786-800.

Werner A, Kramer A, Reedy C, Bebber MR, Pargeter J, Eren MI. Experimental assessment of proximal-lateral edge grinding on haft damage using replicated Late Pleistocene (Clovis) stone projectile points. Archaeological and Anthropological Sciences 2019;11(11):5833-49.

Wragg Sykes R. To see a world in a hafted tool: birch pitch composite technology, cognition and memory in Neanderthals. In Coward F, Hosfield R, Pope M, Wenban-Smith F (editors), Settlement, Society and Cognition in Human Evolution: Landscapes in the Mind 2015 (pp. 117-137). Cambridge: Cambridge University Press.

Yaroshevich A, Nadel D, Tsatskin A. Composite projectiles and hafting technologies at Ohalo II (23 ka, Israel): analyses of impact fractures, morphometric characteristics and adhesive remains on microlithic tools. Journal of Archaeological Science 2013;40(11):4009-23.

Zipkin AM, Wagner M, McGrath K, Brooks AS, Lucas PW. An experimental study of hafting adhesives and the implications for compound tool technology. PLoS ONE 2014;9(11): e112560.