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Experimental assessment of Neo-Assyrian bronze arrowhead penetration: An initial study comparing bilobate versus trilobate morphologies

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ABSTRACT

Archaeological evidence shows that Neo-Assyrian soldiers used multiple arrowhead styles in their weapons arsenal. Indeed, finds from the site of Ziyaret Tepe, located in southeastern Turkey, show that both bilobate and trilobate arrowheads were found in association. Of interest to this study are the factors promoting the invention and perseverance of the trilobate arrowhead form. Manufacturing a trilobate point would have been more costly in both raw materials and energy needed to cast a complex three-dimensional form compared its bilobate counterpart. When considered from an economic standpoint, this generates questions regarding the factors that may have promoted the use of the more complex trilobate arrowheads. To better understand the development of trilobate forms, we began a series of experiments designed to assess the comparative functional efficiency of socketed bilobate versus the socketed trilobate arrowheads made from bronze. This initial study is the first in a long-term experimental program designed to understand variation in performance between arrowhead types. This foundational study focuses on an isolated variable—arrowhead penetration depth— in order to establish a baseline parameter for designing future studies in this series. Our results show that morphology does play a role in arrowhead performance, with bilobate forms penetrating significantly deeper into the target material, however, these results do not explain the functional benefit of the trilobate morphology.

1. Introduction

Archaeological evidence shows that Neo-Assyrian soldiers used multiple arrowhead styles in their weapons arsenal (Dezső, 201898–103; Hellmuth: 1–8, 2014; Miller et al.: 189, 1986; Szudy: 228–235, 2015). Indeed, in several Iron Age Near Eastern contexts arrowheads have been found that differ not only in morphology, but also in raw material. Most arrowheads were manufactured from bronze while some arrowheads were manufactured from iron (Koroglu and Konyar, 2008; Şenyurt, 2006; Summers, 2017). Specifically, finds from the site of Ziyaret Tepe, located in southeastern Turkey, show that both bilobate and trilobate arrowheads were found in contextual association with one another (Matney et al., 2017: 186–189). This contextual evidence suggests simultaneous use of various arrowhead morphologies during the first millennium BC, with the two most common arrowhead morphologies being bilobate or trilobate forms (Szudy, 2015).

Of interest to this study are the factors promoting the adoption and perseverance of trilobate arrowhead forms. Both bilobate and trilobate arrowheads can be manufactured from iron or bronze and both morphologies are found, sometimes contemporaneously, in the archaeological record. Here, in order to minimize the number of variables while focusing on a form that was readily available to Neo-Assyrian archer, we assessed the functional efficiency of the socketed bilobate versus the socketed trilobate arrowheads made from bronze. While larger socketed points created from iron existed at the time, smaller items like arrowheads were primarily created from cast bronze (Szudy, 2015: 156–158, 160–162). Manufacturing a trilobate point would have been more costly in both raw materials and time energy needed to cast a complex three-dimensional form compared its bilobate counterpart, which would have been simpler to cast in a standard two-part mold (Szudy, 2015:

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151–162). When considered from an economic standpoint, this generates questions regarding the factors that may have promoted the use of the more complex and expensive trilobate arrowheads.

Modern arrowhead forms are designed and used for specific purposes related to the type of game being hunted, type of bow being used, and the environmental conditions of the hunt (Hulit: 130–133, 2002; Karger et al.: 496, 1998; Loades: 65, 2016; Szudy: 158–160, 2015). Thus, we can assume that ancient archers were also selecting specific arrowhead forms in order to achieve specific functional goals. Recent experimental studies, primarily focused on stone projectile points (Bebber et al., 2017; Mika et al., 2020; Anderson, 2010) have demonstrated that ancient projectiles were carefully designed to achieve specific goals, often related to penetration efficacy. Unfortunately, although much experimental research has been devoted to stone weaponry, there is a dearth of experimental studies on Bronze Age projectiles (although see (Hulit, 2002; Miller et al., 1986) for examples). To remedy this, here we begin the first of a series of controlled archaeological experiments designed to elucidate the performance characteristics of Neo-Assyrian projectile weaponry. We begin by assessing what is perhaps the most straightforward performance attribute, comparative penetration depth, between two distinct yet contemporary arrowhead morphologies, bilobate versus trilobate socketed, bronze arrowheads (Fig. 1).

Although fully understanding the myriad factors that may have stimulated and maintained cultural variation is a challenge, we have begun this process here by initiating the first in a series of controlled ballistics experiments designed to assess comparative functional efficiency between two distinct arrowhead morphologies to see if they, by virtue of morphology alone, have differing penetration capabilities.

2. Materials and methods

2.1. Ziyaret Tepe

The arrowheads used in this study were modeled on Neo-Assyrian artifacts found at Ziyaret Tepe. Ziyaret Tepe is a multiperiod site located on the Tigris River in the modern-day Diyarbakır Province of southeastern Turkey. Occupation at Ziyaret Tepe was nearly continuous from the Early Bronze Age (c. 3000BCE) to the fall of the Assyrian Empire in the late 7th century BCE, with sporadic later occupation in the Late Iron/ Hellenistic (3rd century BCE to 1st century CE), Late Roman (late 4th to mid-6th century CE) and Medieval periods (late 13th to early 15th century CE). At its maximum size in the Neo-Assyrian period, Ziyaet Tepe (ancient Tušhan) was 32 ha in area with extensive fortifications, temples, residences and a palace perched atop the citadel mound overlooking the surrounding plain.

Of importance to this study, the site spans the transition from the end of the Late Bronze Age through the middle Iron Age (Matney et al., 2017: 29–30). Ziyaret Tepe was first transformed from a small village into a significant provincial city after this region of the upper Tigris River valley was incorporated into the Middle Assyrian empire in the late 13th century BCE Following a decline in imperial power in the mid-11th century BCE, the region was abandoned by the Assyrians for roughly 170 years. The resurgent Neo-Assyrian empire under king Asshurnasirpal II recaptured the upper Tigris River valley and rebuilt the city to serve again as a provincial center. During the intervening period between the two imperial phases, the Early Iron Age, Ziyaret Tepe appears to have been only sparsely occupied, perhaps even used seasonally, by the indigenous populations previously displaced by the Assyrian invaders (Matney and Yener, 2013).

During the excavations at Ziyaret Tepe between 1997 and 2014, twenty-six metal arrowheads or fragments of arrowhead were recovered. Of these, eight were made of bronze (copper or copper alloy) and eighteen were made of iron. They ranged in date based on their findspots from the Middle Assyrian (c. 1300–1050 BCE) to the Medieval period; and only ten were found in secure primary contexts. The most easily identifiable group are five bronze, socketed arrowheads from Neo-Assyrian contexts. Two tanged bronze bilobate arrowheads were found, one in a secure Middle Assyrian context and the other in a mixed context. Only four iron arrowheads came from secure Late Assyrian contexts. Three of these were bilobate, with one being so fragmentary that it cannot be reconstructed with certainty. Three iron trilobate arrowheads were found, but none were from secure primary Late Assyrian contexts, although one came from a Late Iron Age or Hellenistic context. These examples show that both bilobate and trilobate forms were in use in the Late Assyrian city of Tušhan, and that both bronze and iron were being used. The general pattern evident here, despite a small sample size, was that the trilobate arrowheads were made of cast bronze, while the bilobate arrowheads were made of forged iron.

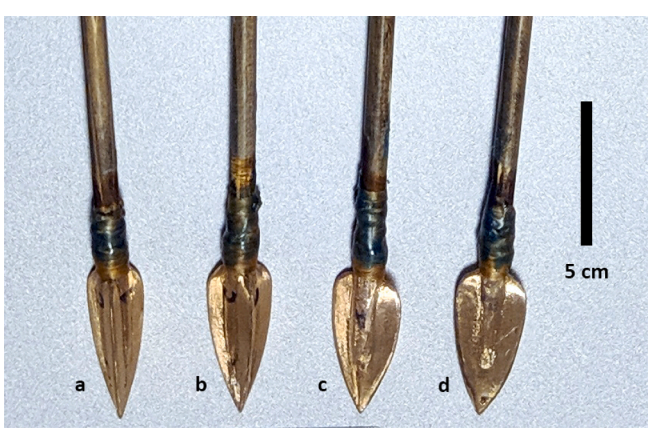

Fig. 1. Replica bronze arrowheads hafted to shafts: a,b) trilobate; c,d) bilobate.

2.2. Replica bronze projectile arrowhead production

2.2.1. Ancient bronze

Bronze, like most technological innovations and transitions, did not suddenly appear in the archaeological record with the standardized formula of 88–89% copper and 8–12% tin which is a global standard today (National Bronze, 2019). While early evidence of copper smelting is known from various sites from the Caucuses through Iran, Indus, and in Asia, (Courcier, 2014; Hoffman and Miller, 2014; Kienlin, 2014; Nezafati et al., 2006; Nezafati and Stöllner, 2017; Peterson et al., 2016; Thornton, 2014) finds indicating the earliest alloying of copper with arsenic in the region of the Assyrian and Neo-Assyrian empires in the ancient Near East date to roughly the fifth millennium B.C. (Adriaens et al., 2002; Lehner and Yener, 2014; Palmieri et al., 1993; Tylecote, 2002; Vandiver et al., 1992; Zwicker, 1980). Later copper alloys included copper-lead, copper-arsenic-nickel, and copper-arsenic-antimony in the 4th MBC. Finally, in the Near East tin starts to be added to copper to produce tin-bronze as an alloy in the very late or early 3rd millennium BC (Weeks, 2012 : 307–310). While some examples of possible earlier 4th, 5th, or 6th MBC tin-bronzes are cited in the literature, many are of uncertain date, rely upon problematic analyses, or may have been the result of smelting tin-rich copper ore resulting in an "accidental" tin-bronze (Rahmstorf, 2017 185). Examples of these early alloys are found at sites across the region, including Nahal Mishmar, Tepe Gawra, Ur, Amuq, and Abu Matar (Fig. 2) (Moorey, 1988; Tylecote: 12, 2002; Weeks: 307, 2012). The production of copper with a variety of different alloying metals in varying amounts allowed early metalsmiths to create a material that was easier to melt and cast than raw copper and usually harder and more resistant to oxidation. While archaeologists can determine the compositions of the objects created in antiquity, it is more difficult understand how much knowledge of the different materials and combinations nor the level of intentionality employed by ancient smiths when they crafted the items.

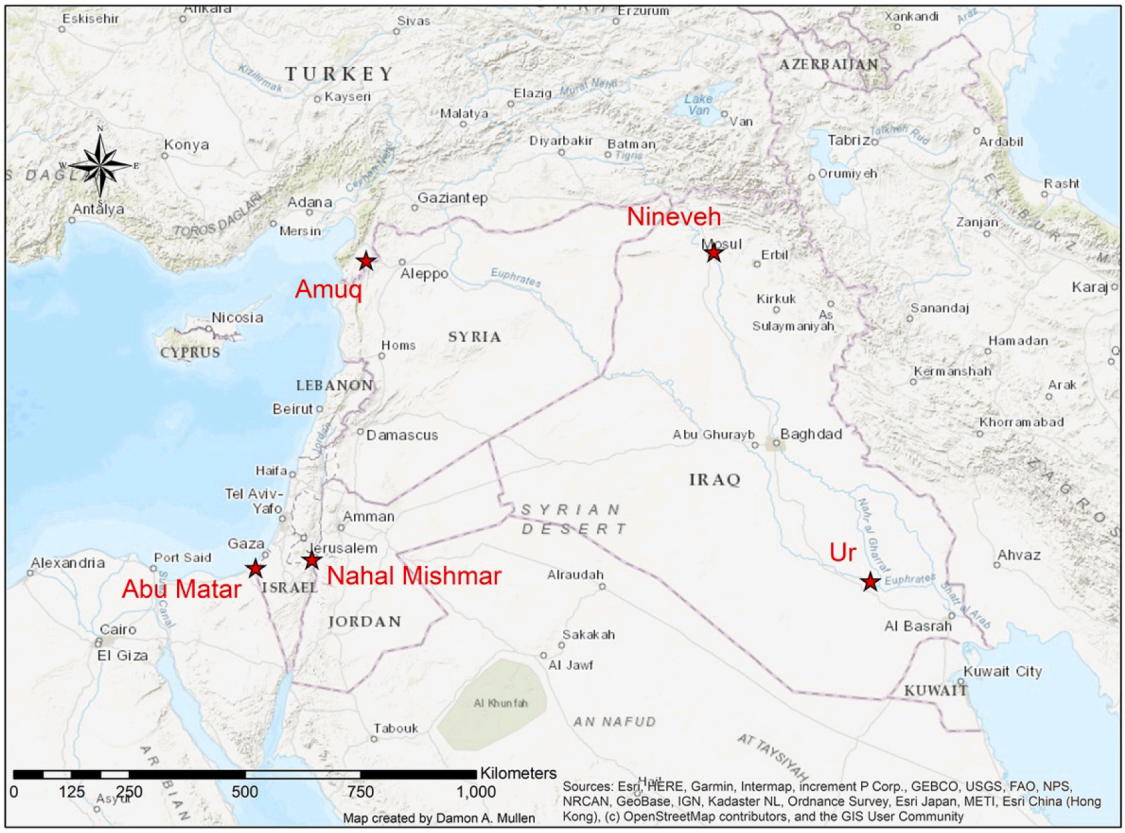

Fig. 2. Map of the ancient Near East showing the locations of early bronze alloying sites: Nahal Mishmar, Tepe Gawra, Amuz, and Abu Matar.

2.2.2. Bronze used in replication

Because some of the mixtures would be too dangerous to create with the tools and facilities available to us in this project (e.g., arsenic), a standard composition of 90/10% copper to tin was used. University of Akron metalsmith, Alex Morrison, crafted four bronze arrowheads, two bilobate, two trilobate, using a modern version of a lost-wax casting technique that was used by Neo-Assyrian craftsman. The bronze that was used to create the arrowheads was derived from previously smelted and cast materials of nearly pure (>99%) tin and copper purchased from a commercial source, RotoMetals of San Leandro, California. The alloy created at the University of Akron in the Mary Schiller Myers School of Art metalsmithing lab had a final composition of 10% tin to 90% copper by weight. Once the arrowheads were completed, they were cleaned and sharpened. Because the sockets of the arrowheads were inconsistent between the samples, they were sent to Michael R. Fisch, Ph.D. of the College of Aeronautics and Engineering at Kent State University to clean, align, and bore the specimens for hafting.

It has been suggested by scholars, specialists, and enthusiasts alike that the mass of a projectile can be a possible determinant of its penetration potential. This is largely due to the ways in which mass affects velocity and kinetic energy (Ashby, 2005; Christenson, 1986; Cundy, 1989; Gottlieb, 2004; Sitton et al., 2020; Szudy, 2015). Other factors, however, such as point morphology – the factor we are interested in here – could also influence penetration Eren et al., 2020; Mika et al., 2020; Sitton et al., 2020). Therefore, in order to isolate and assess the role of arrowhead morphology, without the conflating factor of mass, extra weight was added to the lighter bilobate arrows to ensure all of the arrows had equal weight and thus equal velocity, as described below.

2.3. Bows and shafts

Ancient bow and arrow technology can be difficult to study as both the bows themselves as well as the arrow shafts are often made from organic materials like wood, sinew, and bone; all of which decompose readily and are often lost to the archaeological record. As such, it is often only the arrowheads that are available as artifactual evidence. The following summarizes what is known from textual evidence and ancient artwork depicting the bow and arrow technologies of the Neo-Assyrians and their contemporaries.

2.3.1. Neo-Assyrian arrow shafts

Arrows used by Neo-Assyrian archers were carried in leather, wood, or bronze quivers or bow cases (Szudy, 2015: 110–119). The shafts were composed of unknown materials, though textual records indicate that reeds, possibly fortified with hardwood foreshafts, were likely used in the ancient Near East, as in Egypt (Loades: 68, 2016; Miller et al.: 188–189, 1986; Szudy: 119–121, 2015). Because of the ease with which they deteriorate in the archaeological record, little evidence of actual shaft materials remains, however, one source (Balfour, 1897: 215–217), does indicate that arrows found in an Egyptian tomb with an Assyrian composite bow were indeed made of reed and (Szudy, 2015) discusses multiple sites that indicate reed fibers and pieces of shafts in context with bronze, socketed arrowheads.

2.3.2. Arrow shafts used in experiment

Easton Carbon Aftermath brand carbon fiber arrow shafts were purchased from The Complete Hunter's Outlet, LLC in Mogadore, Ohio. The shafts were selected after discussing both the project and the weight of the arrowheads with the employees of the shop. The shafts measure 31.75 in. (80.645 cm) in length with a 9/32 in. (0.714375 cm) outside diameter. The shafts were fitted into the arrowhead sockets using a combination of Gorilla Brand Super Glue, Gorilla Brand GorillaWeld Steel Bond Epoxy (4250 PSI) and Ferr-L-Tite Glue, a modern arrow adhesive. SummerHouse Brand High-Density Lead tape was applied to each bilobate-tipped arrow, directly behind the socket, to add weight and make them consistent with their trilobate counterparts. Black

Gorilla Brand Duct Tape was placed over top of the weighted tape in order to reduce potential drag that may occur upon entering the clay target.

2.3.3. Neo Assyrian bow

Our current knowledge of bows from the Neo-Assyrian period is gleaned primarily from reliefs and texts, though some examples have survived the archaeological record, most notably from the tomb of the Egyptian pharaoh, Tutankhamun (Loades, 2016: 12) and another tomb of the twenty-sixth dynasty excavated by Flinders Petrie (Balfour, 1897: 210–211). These surviving records and the artefactual evidence have provided sufficient evidence for modern bowyers to create replicas that provide a general idea of the bow shape, how they worked, and the power of their pull.

The Neo-Assyrians used single-stave, self-bows made with a single piece of wood as well as a variety of composite and recurve bows made of wood, bark, sinew, and horn or bone; with the recurve most often depicted during the reign of Assurnasirpal II (Loades: 12, 2016; Miller et al.: 179–185, 1986; Szudy: 106–109, 2015). Replica bows, created by modern bowyers who specialize in making bows from traditional techniques and with materials that mimic the original have shown that Neo-Assyrian composite recurve bows had a draw-weight of roughly 75lbs, yet remained light and easy to maneuver (Loades, 2016:12).

2.3.4. Bow and target used in the experiment

The arrows were fired at The Kent State University Experimental Archaeology Laboratory at Kent State University, using a 29 lb draw Microburner MX model compound bow produced by PSE (Precision Shooting Equipment), Inc. The hafted projectile specimens were fired into blocks of moist clay containing crystalline silica, which has been used as an ethical substitute for meat and tissue in other studies (Key and Lycett, 2017; Key et al., 2018; McGorry et al., 2004). The clay was wrapped in plastic and left in its manufactured state for both consistency and to retain moisture. It is worth noting that although several studies have used ballistics gel as a target material for stone weaponry research (Anderson, 2010; Milks et al., 2016; Waguespack et al., 2009; Wilkins et al., 2014; Wood and Fitzhugh, 2018), it has been demonstrated that ballistics gel may not be well suited for assessing the penetration ability of metal arrowheads (Karger et al., 1998), due to how easily metal tips slice through the ballistic gel target material. In contrast, clay offers an affordable, ethical target material that offers similar resistance to biological tissue (Key et al., 2018).

2.4. Experiments

Our experiment here follows closely the procedures described in Bebber and Eren (2018), Bebber et al. (2020), Lowe et al. (2019), and Werner et al. (2019), and much of what follows in this section has been reproduced from those studies with appropriate and specific modifications for the present study.

2.4.1. Experimental setting

For this experiment, in lieu of a more externally valid (Eren et al., 2016) human archer, we chose a more internally valid, highly controlled approach using a bow tuning machine. The bow was mounted to a Spot-Hogg "Hooter Shooter", designed for calibration of compound bows; but here used to control the consistency of the pull weight. The bow-tuning machine was originally designed for calibration of compound bows. However, its use here facilitated high experimental control of pull weight, projectile velocity, and firing direction in a safe and consistent manner without risk of human error influencing the results. The device fired each arrow a distance of 2.75 m to measure velocity, a Gamma Master Model Shooting Chrony Chonograph was used throughout the experiment.

2.4.2. Firing procedure and measuring penetration depth

Each of the four arrows, two bilobate and two trilobate (Fig. 1), were fired into the clay target 30 times, totaling 60 shots for each arrowhead morphology, and 120 shots *in toto*. The arrows were fired in successive order, #1–4, in 30 rounds. The arrows were fired in ordered rounds to control for any minor changes in room temperature, humidity, or target material. Penetration depth into the clay target was recorded for each shot. This variable was measured by marking the shaft at the location at which the shaft was first exposed and not embedded in the clay target. Once the specimen was removed, a tape measure was used to measure from the mark on the shaft to the tip of the arrowhead. The measurement was recorded in centimeters and each specimen had a total of 30 depth of penetration measurements.

3. Results

The average penetration depth for bilobate bronze arrowheads is deeper than trilobate bronze arrowheads (Table 1; Fig. 3). The variation in both sets of penetration depths are similar and means and medians are close in value suggesting the sample distributions are normal. Shapiro-Wilk tests confirm the normality in these samples (bilobate $W = 0.982$, $p = 0.514$; trilobate $W = 0.982$, $p = 0.533$). A two-sample t test reveals a significant difference in penetration depths with bilobate arrowheads having deeper penetration depth on average than trilobate arrowheads ($t = 4.216$, $p < 0.0000$). The difference between these two sample distributions as measured by effect size is large (Cohen's $d = 0.77$).

4. Discussion

Our results show that morphology does play a role in arrowhead performance, with bilobate arrowheads penetrating significantly deeper than their trilobate counterparts. This result is not entirely unexpected given the reduced surface area and thus lower resistance of the bilobate arrowheads (Eren et al., 2020; Mika et al., 2020; Sitton et al., 2020). However, these results, though significant in this study, may not have been readily apparent to ancient archers, as the difference in penetration depth is on average little more than 1 cm. This presents further questions related to the conditions in which an archer would notice the loss of ~ 11 mm in penetration depth (Waguespack et al., 2009). Likewise, these results do not explain the functional advantage of trilobate arrowheads nor what factors were involved in their widespread adoption starting in the 7th century BCE (Muscarella, 2006: 157). Indeed, our results generate several further questions related to both performance end goals and weapon production economy.

While the technological skill to work iron into arrowheads was available in the Neo-Assyrian period and the raw materials more plentiful, its greater economic value over bronze at the time and the types of sockets that it could be formed into were not ideal for creating small arrowheads (Szudy, 2015: 156–158). It can be assumed that manufacturing a bronze trilobate arrowhead would have been more costly in several ways than fashioning a bronze bilobate arrowhead when taking into consideration raw material acquisition, mold production, time energy, and craftsperson skill that would have been

Table 1
Summary statistics for 60 experimental penetration depths of bilobate and trilobate bronze arrowheads. Values in parentheses are bootstrapped confidence limits.

	Bilobate	Trilobate
Min	19.4	18.5
Max	25.6	24.9
Mean	22.19 (21.82–22.54)	21.18 (20.88–21.47)
Stand. dev	1.43	1.18
Median	22.15	21.25
Coeff. var	6.46	5.56

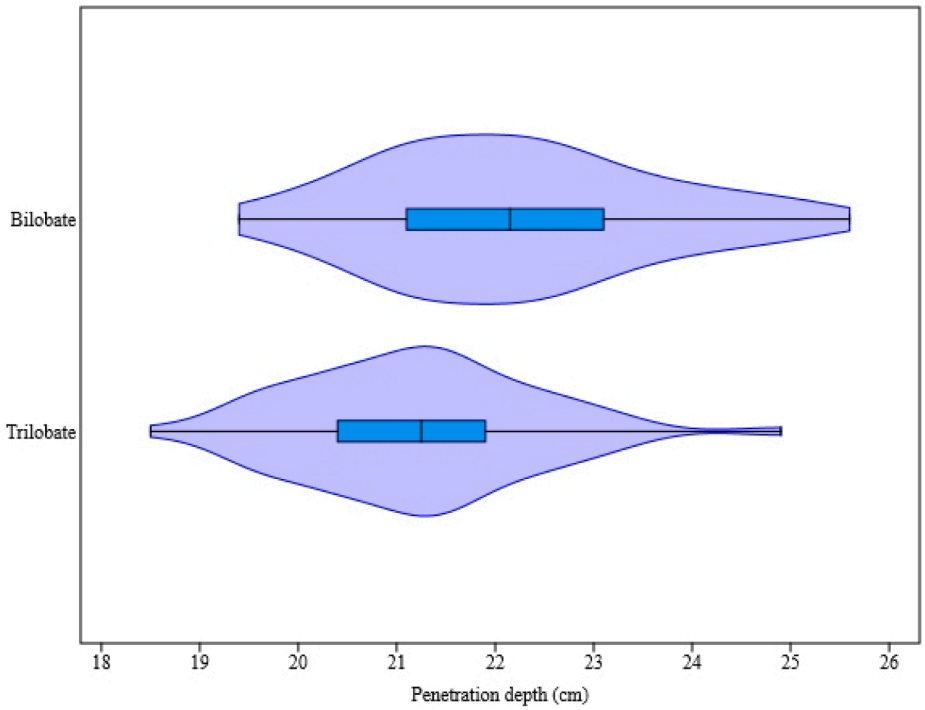

Fig. 3. Box and violin plot of the experimental bilobate and trilobate arrowhead penetration depth data in centimeters.

needed to cast a complex three-dimensional form. Whereas, in contrast, its bilobate counterpart would have been simpler to cast in a standard two-part mold (Szudy, 2015: 151–162). When considered from an economic standpoint, this generates further questions regarding the factors which may have promoted the use of the more expensive trilobate arrowheads. What was their advantage?

In reality, several other factors may have been at play during the "Iron Age arms race" as armor and weaponry co-evolved (Hulit: 17–59, 2002; Szudy: 159–160, 2015). For instance, it could be that penetration depth was not needed beyond a certain threshold (i.e. once a minimum depth was achieved, the enemy would have been debilitated). Likewise, as certain armors became more common, there was likely a need for more durable arrow tips. Trilobate arrowhead tips may offer a significant durability advantage compared to the tip of a bilobate arrowhead. Subsequent tests will evaluate durability metrics between bilobate and trilobate arrowhead tips as well as the interrelationship between armor and arrowhead type.

Another factor that could be affecting selection for trilobate arrowheads is wound size (Karger et al.: 500, 1998; Loades: 65, 2016; Szudy: 261, 2015). Though not measured here, it was noted that the trilobate arrows appeared to leave noticeably larger and likely more destructive cavities in the clay matrix. In future studies, measurements to quantify wound patterns (Anderson: 41–43, 2010; Karger et al.: 497–500, 1998) and severity left by each arrowhead type will be conducted. Tests of other aerodynamic and performance properties of the different arrowhead styles and materials will also be conducted, such as aerodynamics, which Wright (2008: 27–28) suggests is influenced by the position of the lobes on the trilobate arrowhead, thus granting greater precision in flight than the bilobate arrowheads. Keeping the overall length of the arrowheads the same, trilobate arrowheads would naturally weigh more than the bilobate arrowheads and, at similar velocities, be expected to penetrate further. Tests of each type conducted at natural weights will be conducted at the same velocities (requiring different pull weights) and at similar pull weights (resulting in different velocities) to understand the variations in penetration specifically resulting from arrowhead morphology. Likewise, in our next series of tests, varying physical characteristics beyond weight (size, other morphologies, etc.) will be conducted to clarify how they affect overall performance. These initial experiments are highly controlled and thus offer high internal validity for which to build upon (Eren et al., 2016; Lycett and Eren, 2013; Mesoudi, 2011). However, although useful, we acknowledge that experiments using modern materials are far removed from the archaeological record, thus, future testing will replicate the technologies and materials (bitumen adhesives, bronzes with varying compositions, iron arrowheads, tangs versus socketed types, etc.) available to ancient peoples (Balfour, 1897: 216–217) to better replicate the conditions and context in which they were chosen and adopted. Similarly, now that we have baseline penetration data comparing arrowhead morphologies in a highly controlled setup, a similar study could be done using human archers at a great distance to better understand how arrows lose velocity over distance and how morphology may affect target accuracy.

No experiment is perfect, and although the research presented here has several limitations, this initial study is the first in a long-term experimental program designed to understand variation in performance between competing arrowhead types. This initial study focused on an isolated variable—arrowhead penetration depth— in order to establish a baseline parameter for designing future studies in this series. In closing, it should be noted that attempting to understand the interrelationships between arrowhead morphology, raw material choice, and the needs of ancient archers is a complex endeavor. However, it is a problem that can be addressed using experimental archaeology to isolate and systematically assess basic performance variables, and then building upon preliminary results over time. In such a manner, subsequent research designs can effectively unravel the complex, interrelated nature of material culture evolution.

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CRediT authorship contribution statement

Damon Mullen: Conceptualization, Investigation, Writing - original

draft, Writing – review & editing. **Timothy Matney:** Conceptualization, Writing – review & editing. **Alex Morrison:** Resources, Investigation. **Michael Fisch:** Methodology, Resources. **Briggs Buchanan:** Formal analysis, Writing – review & editing. **Michelle R. Bebber:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing – review & editing.

Declarations of interest

All authors declare no conflict of interest.

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