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Experimental evidence for the efficacy of transversal hafting of backed segments as arrowheads

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ABSTRACT

Backed segments in quartz from the Howiesons Poort industry of Southern Africa (65–60 ka) have been interpreted as tips of arrows. Nevertheless, several different hafting configurations for these pieces have been proposed. Here, experimental data on the efficacy of two different hafting configurations is presented. Arrows with flint segments replicated to the dimensions of quartz segments from the Howiesons Poort have been shot into gelatin targets. These experiments show that transversally hafted segments outperform diagonally hafted segments in penetration depth, but there is substantial overlap in the size of wounds caused. Our results help constrain the interpretation of archaeological backed segments from the Howiesons Poort and similar lithic elements from technocomplexes across Africa and Europe.

1. Introduction

Reconstructing the exact functioning of hafted lithic pieces when their organic hafts have not been preserved presents formidable challenges. Experimental archaeology can provide important information on the functional efficacy of different proposed hafting configurations and uses. Here we present experimental data on the efficacy of two distinct hafting configurations of backed lithic pieces.

Backed, semi-circular lithic artefacts are known from a number of Stone Age technocomplexes around the world. Such elements are characteristic of the Howiesons Poort technocomplex in Southern Africa conventionally dated to ∼ 65–55 ka (e.g., Lombard et al., 2022; Lombard et al., 2012). Howiesons Poort segments have long been suggested to function as parts of weapon systems, such as inserts for spearheads (e.g. Deacon 1989), barbs on weapons (e.g. de la Peña et al. 2018), and arrow tips (e.g., Lombard, 2011; Lombard & Phillipson, 2010). Several different hafting configurations have been proposed for Howiesons Poort segments functioning as arrow tips, as well as for similar lithics from the East Africa pastoral Neolithic and the Kebaran (see e.g., de la Peña et al. 2018; Goldstein & Shaffer, 2017; Lombard & Pargeter, 2008; Pargeter, 2007; Yaroshevich et al., 2010). Suggested hafting configurations include transversal hafting, and diagonal hafting, among others (Fig. 1). Other functions have also been proposed, such as the segments functioning as inserts for knives (Igreja and Porraz 2013). Besides the varied proposed functions, the segments are also argued to have been imbued with symbolic meaning (e.g. Wurz 2008). We test the functional plausibility of the hypothesis that the segments functioned as arrow tips.

Typologically similar artefacts from other archaeological contexts have been also been interpreted as arrowheads, such as the Wilton (southern Africa, 8–2 ka); the East African pastoral Neolithic (3.2–1.2 ka); the Kebaran in the Levant (14.5 – 11.5 ka); the Uluzzian (Mediterranean Europe 45–40 ka) and the Mesolithic (NW Europe 12–5 ka) to name a few (Deeben & Niekus, 2016; Goldstein & Shaffer, 2017; Sano et al., 2019; Yaroshevich et al., 2010).

The interpretation of Howiesons Poort quartz segments as arrow tips rests on multiple lines of evidence. First, there are ethnographic analogies of similarly shaped artefacts as arrow tips (e.g. Wurz 1999). Second, the correspondence of metric dimensions and Tip Cross-Sectional Area (TCSA) values of the Howiesons Poort segments with those of ethnographically documented arrowheads is argued to support their use as arrow tips (e.g. Lombard 2020). Third, use-trace analysis of these artefacts has been used to argue that they functioned as arrowheads (e.g., Lombard, 2011; Lombard & Phillipson, 2010, also see Wurz 2008). Other scholars have argued against this interpretation, highlighting poor reliability of the use-trace evidence, especially in quartz. The problem of

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equifinality of traces produced under different functions (e.g. use as tips or barbs can result in similar traces being produced on the piece) is also highlighted (e.g. Fernández-Marchena and Ollé, 2016; Rots et al., 2017; Taipale et al., 2022; Taipale and Rots, 2019; Villa et al., 2012). Hence, experimental evidence on whether the proposed interpretations are functionally feasible can provide valuable supplementary evidence for the interpretation of archaeological segments.

Experimental studies have been conducted to test the efficacy of proposed interpretations. For the Howiesons Poort, Pargeter and Lombard (Lombard & Pargeter, 2008; Pargeter, 2007) have performed experiments shooting arrows hafted with backed segments. They state that the pointed hafting configuration penetrates an animal carcass better than the transversal configuration. However, an experiment for Kenyan pastoral Neolithic segments yielded the opposite result (Goldstein & Shaffer, 2017). Schoville and colleagues (2017) similarly conducted a series of experiments and conclude that diagonal hafting performs better in penetrating the skin of a carcass, but when tested in ballistics gel transversal hafting penetrates more deeply, creating larger wounds.

As backed pieces can be hafted in a variety of ways, the interpretation of archaeological examples is complex. Projectile points are often compared using their Tip Cross-Sectional Area (TCSA), an index proposed to correlate to the penetrative characteristics of weapons (e.g., Hughes, 1998; Lombard et al., 2024; Sisk & Shea, 2011). Based on ethnographic data, specific ranges of TCSA values of lithic implements have been correlated to their use as specific weapon types (e.g. Lombard 2020; Lombard et al. 2024). Yet, the hafting configuration of backed pieces influences the TCSA of the projectile. Lombard (2020) therefore calculates minimum and maximum TCSA estimates for the Howiesons Poort to account for different hafting configurations (Lombard, 2020). Which estimate is most applicable for such pieces remains ambiguous and may be clarified by experimental evidence on the feasibility of different hafting configurations.

Experimental research to-date has concentrated on the identification of characteristic features for the use of lithic implements as arrows, such as diagnostic impact fractures (DIF's) (e.g., Lombard & Pargeter, 2008; Sano et al., 2019), and microscopic evidence for impact such as microscopic linear impact traces (MLITs) (Rots & Plisson, 2014). Very little experimental data is available on the actual performance of similar lithic tools in different hafting configurations (but see Goldstein & Shaffer, 2017; Pargeter, 2007; Schoville et al. 2017; Yaroshevich et al., 2010).

We report an arrow-shooting experiment, designed to differentiate the efficacy of transversal and diagonal hafting of backed segments on gelatin blocks. We test replicas with the dimensions of the Howiesons Poort quartz segments in our experiments. We replicate segments excavated at Umhlatuzana rockshelter (Kaplan, 1990; Lombard et al., 2010; Sifogeorgaki et al., 2020). We test three variables:

- Penetrative power: we measure if transversal or diagonally hafted arrows penetrate deeper
- "Entry wound size": we review which hafting configuration produces bigger "wounds" on targets
- The influence of TCSA on penetrative power and entry wound size: we calculate the TCSA for the different hafting configurations and review its influence on the penetration depth and entry wound size

By keeping all relevant factors aside from hafting configuration as constant as possible, we isolate the influence of hafting configuration on the penetrative power of arrows. This provides important contextual information for the interpretation of archaeological lithics where the hafting configuration cannot be easily reconstructed.

2. Background

2.1. Segments in the Howiesons Poort

The Howiesons Poort technocomplex in South Africa is characterized by the importance of backed segments in the lithic tool inventories (Henshilwood, 2012; Lombard et al., 2022; Lombard et al., 2012). Although the Howiesons Poort is conventionally dated to 65–60 ka (Jacobs et al., 2008), older dates for the technocomplex, going back to 100 ka have been proposed, e.g. for the site of Diepkloof (Porraz et al.,

Fig. 1. Photos of experimental arrows A and C used in the experiments showing the transversal and diagonal hafting configurations.

2013, also see Brown et al., 2012).

The segments in Howiesons Poort assemblages are generally made on blades, but, especially in quartz, have also been produced on bladelets (de la Peña, 2020). They have a straight sharp edge, while the other side is backed using steep retouch (Fig. 2). They come in a wide range of sizes. Wadley and Mohapi (2008) have shown that dimensions of segments at the site of Sibhudu vary according to the raw materials that they are manufactured in. The segments produced in quartz are characterized by the smallest dimensions. The use-trace analysis supporting an interpretation as arrowheads focused specifically on the quartz segments (e.g., Lombard, 2011; Lombard & Phillipson, 2010). Larger segments in other raw materials may have functioned differently.

The identification of Howiesons Poort weapon tips as well as the determination of weapon types often rely on use-trace studies (e.g. de la Peña et al. 2018; Lombard, 2011; Lombard & Phillipson, 2010, see for review of criteria e.g Rots & Plisson 2014, Taipale et al. 2022). Experimental comparisons have been used to suggest that unretouched small pieces, but also segments, have functioned as barbs at Sibhudu (de la Peña et al. 2018). Other studies suggest the use of small quartz segments as arrow tips. The traces to support this interpretation include observations of the remains of ochre-loaded adhesives on the backed side of the segments, demonstrating they were hafted (Lombard, 2007, 2011; Lombard & Phillipson, 2010). Further, microscopic observations of remains of animal matter, as well as macroscopic and microscopic observations of so-called “diagnostic impact fractures” on the sharp edge, suggest their use as projectile weapons (Lombard, 2011; Lombard & Pargeter, 2008; Lombard & Phillipson, 2010). Lombard (2011) suggests based on the location and distribution of wear traces that some segments were hafted transversally and some potentially diagonally.

Proponents of the interpretation of backed segments as arrowheads draw further support for the interpretation of backed segments as arrowheads from a comparison of the TCSA values of quartz segments from the Howiesons Poort with TCSA values from ethnographic collections of known arrowheads (Lombard et al., 2024). However, the precision with which TCSA can be used to determine the delivery system for a point type is contested. Experiments with arrows and darts tipped with points with similar TCSA values show overlap in penetration depth when shot with a crossbow at gelatin targets (Clarkson 2016). Archaeological analyses have also been used to cast doubt on the accuracy of ethnographic comparable data-sets (Coppe et al. 2023). Hence, the interpretation of quartz backed segments should be supported by multiple lines of argumentation including use-trace and other functional evidence.

To take into account that different hafting configurations may impact the TCSA value of the tools, Lombard (2020) calculates two TCSA values, one based on the segment width (the formula usually used for pointed artefacts), and one based on segment length, which covers transversal hafting of the pieces (see Fig. 1). The TCSA values (max TCSA 33 ± 27, min TCSA 16 ± 10; Lombard 2020, Table 4) arrived at for the quartz segments from the Howiesons Poort assemblage from Umhlatuzana (as well as for other assemblages) fall within the range of ethnographically known arrowheads (TCSA range 13–53, Lombard, 2020, Table 1). If they were hafted longitudinally, some segments overlap in dimensions with ethnographic poisoned arrows, which are significantly smaller (TCSA range 4–18, Lombard, 2020, Table 1).

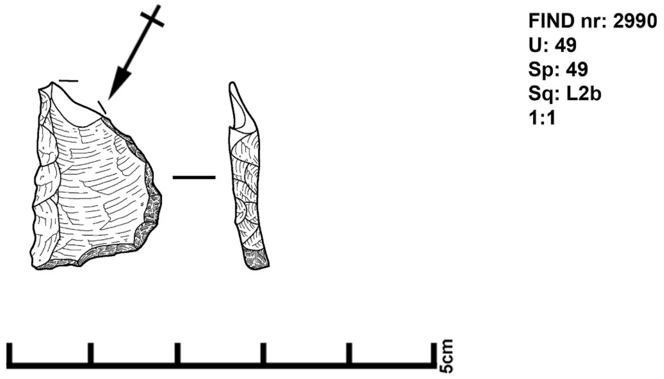

Fig. 2. Drawing of a quartz segment from the late Middle Stone Age at Umhlatuzana rockshelter (see Sifogeorgaki et al., 2020; Sifogeorgaki et al., 2023). Drawing: Tullio Abruzzese.

2.2. *Weapon tip performance*

The function of the lithic tips on projectiles is to ensure the successful creation of a hole that allows the weapon shaft to enter the prey’s tissue (Friis-Hansen, 1990; Hughes, 1998). The penetrative performance of weapon tips depends on five main factors: velocity/force, mass of the tip, size and shape of the tip and drag (Hughes, 1998).

Hughes (1998, 349-350) captures the interplay of these factors into the following equation:

$$\text{Penetration} = MV_0/CA$$

In which:
M = mass.
V_0 = is the velocity at which the target is struck.
C = a dimensional constant.
A = the projectile’s cross-sectional area.
This means that, all other things being equal:

- With increased velocity a point penetrates better
- Heavier tips penetrate better than lighter ones
- Smaller tips penetrate better than larger tips

The projectile encounters drag, both through the air and through tissue. The drag decreases velocity and hence limits the penetration depth. It is formalized by Hughes (1998, 350) as:

$$\text{Drag} = 1/2K_d p\ A\ v^2$$

In which:
K_d = the drag coefficient consisting of a constant for the medium, a shape factor and surface roughness.
p = the density of the medium.
A = the projectile’s cross sectional area.
v = the velocity of the projectile.
This means, in lower-density mediums penetration and with smaller cross-sectional areas penetrative depth will be better. Somewhat counter-intuitively increased projectile velocity also “retard[s] projectile motion, reducing penetration depth” (Hughes 1998, 350).

TCSA is calculated as:

$$\text{TCSA} = 0.5^*w^*t$$

In which:
w = maximum width.
t = maximum thickness.

Sisk and Shea (2011) suggest that TCSA tracks the more relevant variable TCSP, for which they provide two formulas, one geared towards approximating the perimeter of bifacially worked points and one for unifacially worked points. As Howiesons Poort segments are not bifacial, we have calculated the unifacial TCSP as:

$$\text{TCSP} = w + 2\ ^*\sqrt{((w/2)^2 + t^2)}$$

The effect of point size on penetration performance leads to a trade-off. The surface area of wounds determines the lethality and hence larger, deeper wounds will be more effective to bring down larger prey (Friis-Hansen, 1990; Hughes, 1998). The shape of the point influences efficiency in penetration. Friis-Hansen (1990, 497) states that arrow points with a narrow front angle have the best penetrative capabilities.

Table 1
Dimensions of the segments used in the experiments in mm. and TCSA and TCSP values calculated from these values. *substituted length for width, following Lombard (2020) and Wadley & Mohapi (2008) to take into account the hafting configuration. $^+$Underestimate as diagonal hafting configuration yields larger maximum width than the width of the lithic piece.

Segment	Length	Width	Hafted width diagonal arrows	Thickness	TCSA lithic point	TCSA with hafted width	TCSP lithic point
A	16.6	9.1	16	3.9	17.7$^+$	31.2	21.1
B	17.6	8.9	NA	2.5	22*	NA	19.1
C	15.5	8.5	NA	3.3	25.6*	NA	19.3
D	18.9	9.1	NA	3.8	35.9*	NA	21.1
E	17.5	8.8	16	2.7	11.9$^+$	21.6	19.1
F	18.1	9.3		3.6	16.8$^+$		21.1

With duller angles, penetration is less effective.

Recent work demonstrates some additional tip characteristics that have a significant influence on the point's penetration success. Edge sharpness, especially of the tip influences the penetrative power, significantly lowering the force required to puncture skin, putting a premium on the use of fine-grained raw materials as these produce sharper edges (Pettigrew et al. 2023, 21). This measure is more relevant for transversally hafted segments, as they lack a frontal angle. The distance between tip and start of the shaft also has an influence, with longer points penetrating better (e.g. Grady and Churchill 2023; also see Pettigrew et al. 2023). Further, although archaeologically often invisible due to the lack of organic preservation, shaft and haft thickness are of great importance (Pettigrew et al. 2023).

In our experiments we test how different hafting configurations of identically shaped lithic implements influence penetration and entry wound size. In both Hughes' (1998) equations on penetration and projectile drag, as well as in Friis-Hansen's (1990) work on cutting efficiency, the shape of the arrow plays an important role. Diagonally hafted segments provide a narrower front angle and may be expected to have larger cutting efficiency. Yet the indications of transversal hafting of segments from the Howiesons Poort and other technocomplexes stimulate experiments to test how this configuration performs.

2.3. *Shooting experiments*

Shooting experiments using replicas of Howiesons Poort arrows were conducted by Pargeter and Lombard (Lombard & Pargeter, 2008; Pargeter, 2007). They report that the segments performed well when shot at an animal carcass. Diagonally hafted segments were more effective at penetrating the carcass than transversally hafted segments, but measurements for penetration depth and entry wound size were not provided, although one diagonally hafted wound is described as ≥ 40 mm deep (Pargeter, 2007, 150). Further analysis focused on the identification of DIF's and comparing the frequencies in which they occur with their frequencies on archaeological segments (Lombard & Pargeter, 2008).

Schoville and colleagues (2017) also report on shooting experiments with replicated Howiesons Poort backed segments. Their experiments involve shots at both a springbok carcass and a ballistics gel target. In these experiments, transversely hafted and diagonally hafted segments were compared. For the shots at ballistics gel, draw weight and projectile mass were kept constant, while for the larger series of shots at a springbok carcass, draw weight was kept constant, but hafted mass was varied leading to differences in velocity across shots). They report that for shots in the Springbok carcass, where hafted mass was under 100 g, diagonally hafted segments were more likely to puncture the animal skin, in comparison transversely hafted segments ricocheted more frequently (Schoville et al. 2017, 310). For the shots into ballistics gel, transversely hafted segments penetrate more deeply on average (~18 cm) than diagonally hafted segments (~15.5 cm), with little overlap. Further, although no TCSA values are given, no consistent relationship between segment length, or segment length/width ratio and penetration depth was observed (Schoville et al. 2017, 311).

Shooting experiments with replicated Howiesons Poort lithics are also reported by de la Peña et al. (2018) and Taipale & Rots (2019). In their experiments using a pony skeleton encased in ballistic gel as a target, the range of penetration depth for transversely hafted arrows is reported and compared to the ranges for barbed arrows and arrows tipped with convergent points. The ranges for transversally hafted arrows (7 – 19.5 cm) and convergent arrows (6.5 – 16.5 cm) largely overlap, but maximum penetration depth reported for the transversally hafted arrows is larger (Taipale & Rots 2019).

Experiments with similar artefacts were performed by Goldstein and Shaffer (2017). They use replicas of pastoral Neolithic segments, which are globally similar in shape to Howiesons Poort segments. Here, the arrows were shot at ballistics gel. The authors report penetrative depth of several hafting configurations. They conclude that transversally hafted segments penetrate very slightly deeper (13.36 cm) than diagonally hafted (oblique in their terminology) segments (13.3 cm). No indication of the variability of the penetration depths is given. Another shooting experiment with similar lithic types was conducted by Yaroshevich et al. (2010). In these experiments, with arrows shot at a fresh goat carcass, diagonally hafted (oblique in their terminology) arrows penetrated on average 23.0 cm and transversally hafted arrows on average 22.6 cm. No indication of the degree of variability is given.

Most experiments show small differences and the results are slightly conflicting in that Goldstein and Shaffer (2017) report slightly better penetration for transversally hafted arrows, while Yaroshevich et al. (2010) find slightly better penetration for diagonally hafted arrows. The experiment by Schoville and colleagues (2017) reports different effects between shooting at a carcass and at ballistics gel. In the latter medium transversally hafted arrows show much better penetration. To better understand penetrative capability, we performed experiments on a completely homogeneous medium.

3. Materials and methods

3.1. *Experimental arrows*

One of us, an experienced flint-knapper (MR), replicated prehistoric arrows. Backed segments were knapped to approximate the average dimensions of quartz segments from the Howiesons Poort at Umhlatuzana layer 24, reported by Lombard (2020, Supplementary material) in their TCSA analysis (length 17 mm, width 9.7 mm, thickness 3.8 mm). We used flint as this is readily available to us and allows more controlled knapping than quartz (see e.g., Schmidt et al., 2024), allowing the best replication of the segment dimensions. Six segments (A-F) were produced, with dimensions approximating the averages reported for Umhlatuzana. We measured their dimensions before hafting with digital calipers and they fall well within the range of variation of the quartz segment assemblage (Table 1) (also see Van Harderwijk, 2024). We hafted the tips in two different configurations. Tips A, E and F were hafted diagonally, while tips B, C and D were hafted transversally (Van Harderwijk, 2024) (Figs. 1–28, Supplementary materials).

We calculated TCSA values for all arrows. Lombard (2020, also see Wadley & Mohapi 2008) provides both minimum and maximum TCSA calculations for segments to account for the different potential hafting configurations. The maximum TCSA value pertains to transversally

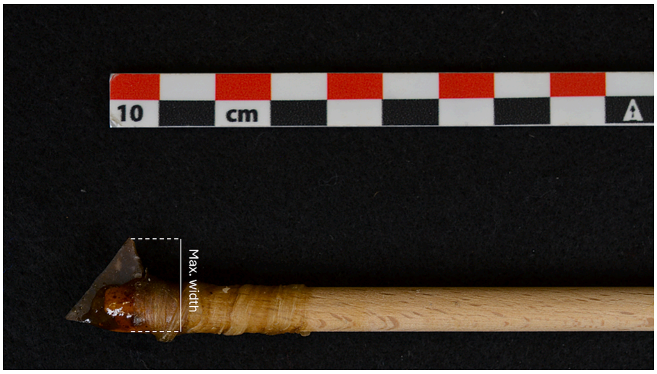

Fig. 3. Photo of diagonally hafted experimental arrow with indication of width measurement taken. For thickness, the value of the lithic piece was taken.

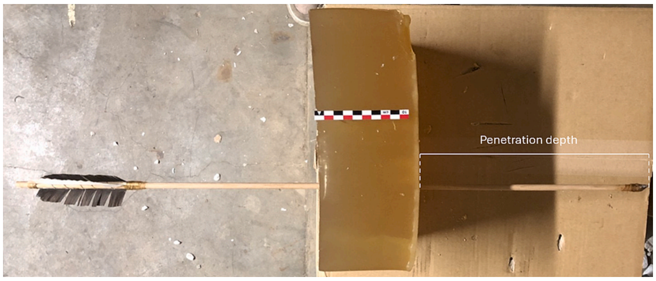

Fig. 4. Photograph of arrow after penetrating the gelatin target indicating the measured penetration depth. Photo: Mick van Harderwijk.

Fig. 5. Photograph of a typical “wound” from an experimental shot. Photo: Mick van Harderwijk.

hafted segments, when the length of the lithic piece represents the maximum width of the projectile point. The minimum configuration represents a fully longitudinally hafted segment, where the width of the lithic piece corresponds to the width of the projectile point.

We use the length of the piece for those pieces that were transversally hafted (following Lombard 2020; Wadley & Mohapi 2008). To estimate the TCSA for segments in a diagonal hafting configuration, we use the minimum estimate and take the width of those pieces. This means that the TCSA values of the diagonally hafted lithic points are underestimates. To compensate for this, and to have comparable data for the transversal and diagonally hafted arrows, we decided to also calculate a TCSA value for the diagonal arrows taking the greatest width of the segments while hafted (see Fig. 3, Table 1). Unfortunately, we took those measurements only after arrow F had shattered during experimentation. After this, we used hand-held calipers for the hafted measurements, providing width at 1 mm accuracy (Table 1). The calculations show there is a considerable difference between the minimum TCSA value and the TCSA calculated on the basis of the actual width for the diagonally hafted pieces. This reinforces previous observations that TCSA values are influenced by the haft and calculating the value from a lithic piece alone may not be informative on the drag encountered by a projectile when entering a target (see Pettigrew et al. 2023).

We also calculated the Tip Cross Sectional Perimeter (TCSP). The latter we have calculated using the formula for unifacial points from Sisk & Shea (2011, 3).

The segments were hafted onto industrially manufactured beech wood rods with a constant diameter of 8 mm, cut at 78.7 cm (31 in) for final shaft configuration. To stabilize them in flight, they were fletched with 3 feathers around the shaft. To ensure consistent orientation of the lithic tip of the arrows for every shot, a different colored cock feather was used on the arrows, at a 90° angle with the string. For all arrows the same combination of prehistoric glue consisting of resin and beeswax (approximately 80–20 % mixture), as well as animal sinew wrapping was used to haft the lithics while the fletching was attached with modern glue. The tip of arrow D broke loose in the second experimental session and was rehafted using superglue for the third session.

3.2. *Experimental set-up*

Following Aleo et al. (2023) we used a handbow, type Geologic Archery Bow Club 500, 68 in., draw weight 26 lbs, to shoot the arrows. To keep the velocity of the shots as constant as possible, we mounted the bow on a mechanical drawing installation, that allowed us to keep the draw length of the bow constant. For all shots, we drew the bowstring to 24 in. (61 cm). We shot the arrows at the target from 2 m distance, to ensure accuracy. We re-measured the distance between the bow and the target before every shot.

We shot the arrows into ballistics gel to try to minimize damage to the points so each could be shot multiple times to document the amount of variability (or lack thereof) in penetration depth and entry wound size keeping all variables as constant as possible. This meant the arrows would penetrate the block fully (Fig. 4), with two advantages:

- Allowing easy measurement of the front part of the arrow that had shot through the block, without having to remove the arrow, which might affect the entry wound size
- Allowing removal of the arrows from the back of the block by “pulling them through”. This precludes the protruding parts of the lithic point from damaging the block, as well as points becoming loose in their hafts during removal

We initially ordered a mineral-oil based ballistics gel, but when testing the experimental set-up found this presented a danger of ricocheting arrows, as was also the case in previous experiments (see Goldstein & Shaffer, 2017; Yaroshevich et al., 2010). To ensure the safety of the experiments, as well as to prevent damage to the arrows, we

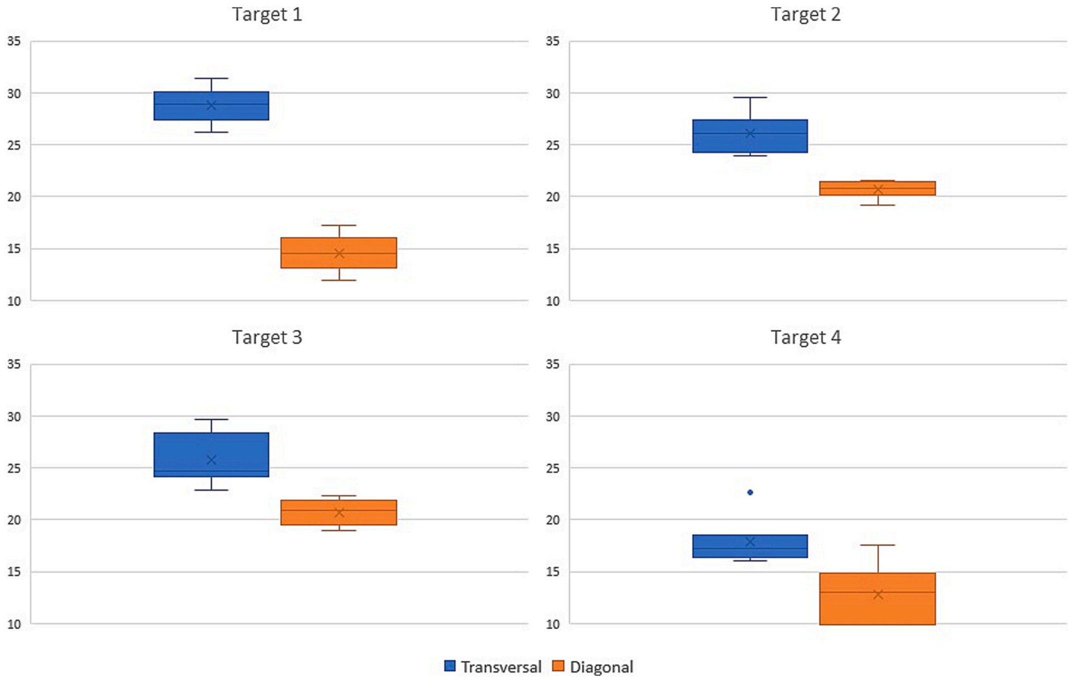

Fig. 6. Box-and-whisker plot showing penetration depth per arrow type per target.

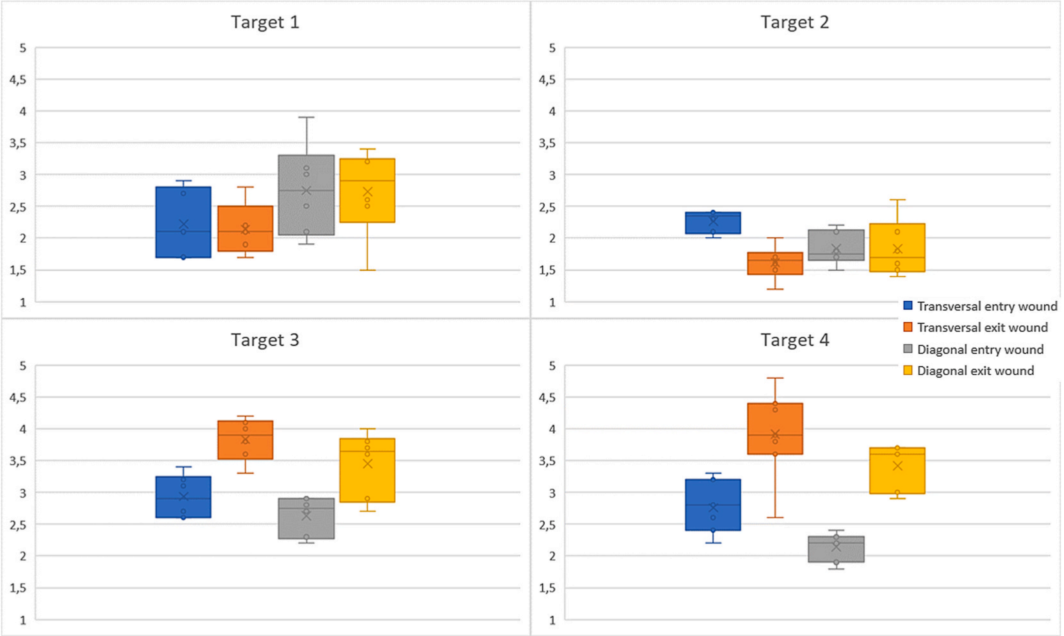

Fig. 7. Box-and-whisker graphs of entry and exit wounds per target.

decided to manufacture gelatin blocks for the experiments, of which the density could be more easily controlled using granulated beef gelatin, 250 bloom (Inka Foods). We used 667 g of gelatin and 6 L of water per block (11 % gelatin). The gelatin was poured into rectangular boxes and chilled overnight to harden. This yielded firm blocks of gelatin, but upon shooting this never resulted in a ricochet. This set-up thus allowed us to clearly observe differences in performance for the different hafting configurations across a homogeneous medium.

The blocks of gelatin were put upright, with steel supports behind to ensure the force of the impact of shooting would not topple them. Using calipers, for each shot, we measured the length of the arrow, including the tip that penetrated the block at the back of the target (Fig. 4). We also measured the thickness of the gelatin block at the point of penetration. Finally, we measured the size of the entry and exit "wounds" (Fig. 5) (Van Harderwijk, 2024).

3.3. *The experiments*

To ensure comparability of the results, we used both hafting types at the same block for six shots each. The different containers for the gelatin differed slightly in shape leading to small differences in thickness between targets. To exclude the influence of small differences in consistency and thickness between blocks we present the results for the different targets separately.

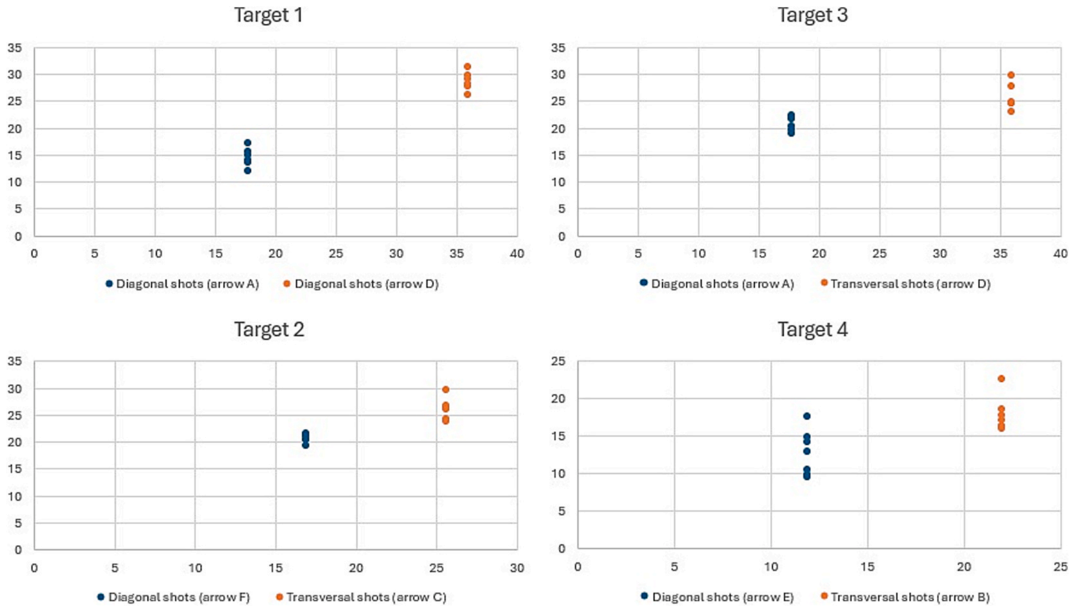

Fig. 8. Comparison of lithic TCSA and penetration depth.

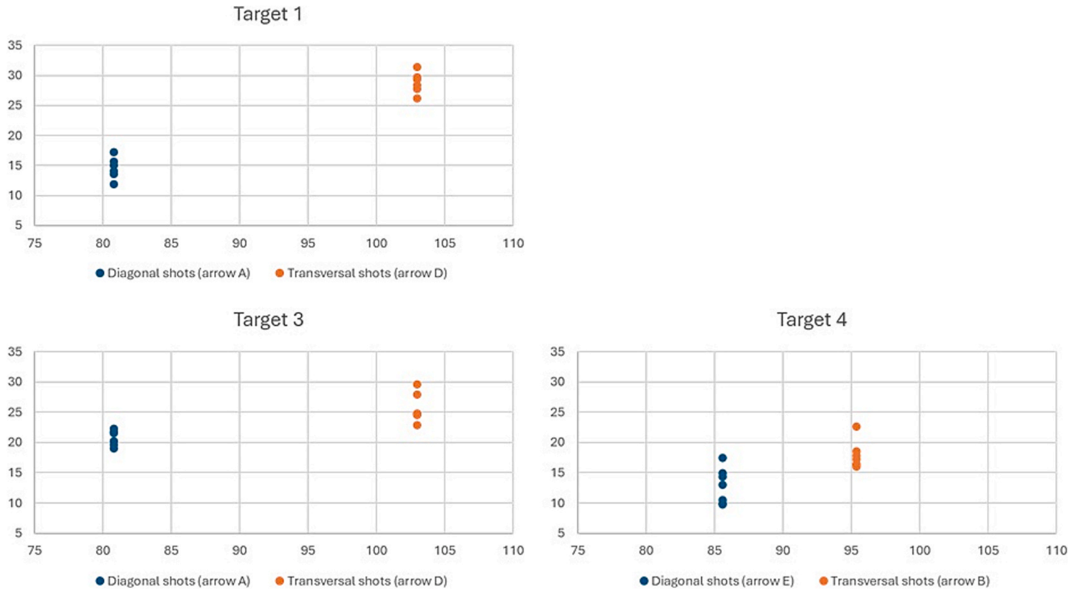

Fig. 9. Comparison of hafted TCSA with maximum joint thickness and penetration depth (See Table 2). Note that for target 2, no measurement of joint thickness could be taken as arrow F had shattered.

We held three experimental sessions, on 14, 20 and 25 March 2024. During the first session we compared arrows A (diagonal, 6 shots) and D (transversal, 6 shots) in one target and arrows F (diagonal) and C (transversal) in another. The session of 20 March was unsuccessful, as two arrows were damaged during the session. This resulted in the second experiment not yielding a dataset of the two different hafting configurations aimed at the same gelatin target. First, arrow F (diagonal) hit the steel support on the second shot, shattering on impact. This is the reason that no TCSA value for this arrow could be calculated (Van Harderwijk, 2024). After a further series of shots with arrow A (diagonal, 8 shots), arrow D (transversal) broke on the third shot. At this point, there was not enough undamaged area of the target to produce a full dataset with a replacement transversal arrow and the experiment was abandoned. On 25 March we compared the rehafted arrow D (transversal, 6 shots) and arrow A (diagonal, 6 shots) in one target and arrow B (transversal, 7 shots) and E (diagonal, 7 shots) in another. This corresponds to 25 shots with a transversally hafted arrow and 25 shots with a diagonally hafted arrow.

During the third session we monitored the temperature in the experimental space to ensure that temperature fluctuations do not influence the consistency of the gelatin blocks. The temperature was constant during the entire session, fluctuating between 20.4 and 20.9 °C (Van Harderwijk, 2024). During the third session, one of the targets used was a remelted target from the first session. Due to some material being lost with the first experimental session, it is slightly thinner than that of the “fresh” targets, but the experimental results are comparable to the other targets (Table 3).

4. Results

Four successful series of shots by both transversally and diagonally hafted arrows in the same target were produced. We present the results

Table 2
Hafted arrow properties. The measurements were taken after the experiments. Data from arrow F is missing as the tip shattered during experimentation.

Arrow	Hafted Weight (grams)	Hafting inclination (degree)	Frontal angle (degree)	Edge angle (degree)	Hafted max. width diagonal arrows (mm)	Max joint thickness (mm)	TCSA with max joint thickness
A	29.4	54	65	NA	16	10.1	80.8
B	28.9	90	NA	31	NA	10.8	95.4
C	32.4	90	NA	30	NA	10.7	82.9
D	32.8	82	NA	35	NA	10.9	103
E	27.6	53	56	NA	16	10.7	85.6
F	NA	NA	NA	NA	NA	NA	NA

Table 3
Average penetration depth and standard deviation and target thickness at point of impact per series of shots in the different targets used. *The target thickness was not measured for the 5th shot in the series. The results of the unsuccessful experiments are omitted here.

	Average penetration depth (cm); SD	Target thickness at point of entry (cm); SD
Target 1		
Arrow D (transversal)	28.8; 1.77 (n=6)	10.7; 0.1
Arrow A (diagonal)	14.57; 1.81 (n=6)	11.2; 0.2
Target 2		
Arrow C (transversal)	26.12; 1.98 (n=6)	11.2; 0.1
Arrow F (diagonal)	20.68; 0.86 (n=6)	10.9; 0.4 (n=5)*
Target 3 (remelted)		
Arrow D (transversal)	25.72; 2.5 (n=6)	9.8; 0.1
Arrow A (diagonal)	20.73; 1.32 (n=6)	9.8; 0.2
Target 4		
Arrow B (transversal)	17.84; 2.95 (n=7)	11.0; 0.3
Arrow E (diagonal)	12.83; 2.27 (n=7)	10.9; 0.3

in terms of penetration, entry and exit entry wound size.

4.1. Penetration

In all the blocks, the transversally hafted arrows penetrate further than the diagonally hafted arrows, so much so that there is virtually no overlap in the penetration depth (Fig. 6, Table 2, see supplementary table for full dataset) (Van Harderwijk, 2024). During each session there is no progressive increase in penetration depth, showing that weakening of the blocks due to previous shots did not affect the results (supplementary figure 29).

4.2. Entry and exit wound

For the entry and exit wounds we measured the maximum dimension (length) and the width. The width was generally the width of the arrow shaft (8 mm), but the maximum dimension exhibited much greater variation.

The transversally hafted arrows may create slightly larger entry and exit wounds, but the pattern is far from clear. The range of variation expressed by the standard deviation is relatively large and entry wound size substantially overlaps for most series comparing the two hafting configurations (Fig. 7, Table 4) (Van Harderwijk, 2024).

4.3. TCSA

In our analysis of the relationship between TCSA and penetration, for the diagonally hafted arrows, we use the TCSA values based on the hafted segments instead of the minimum estimates based on the width of the lithic piece alone.

Table 4
Summary of entry wound size data per target.

	Average max dimension entry wound (cm)	St. dev.	Average max dimension exit wound (cm)	St. dev.
Target 1				
Arrow D (transversal)	2.22	0.56	2.14	0.42
Arrow A (diagonal)	2.75	0.74	2.73	0.7
Target 2				
Arrow C (transversal)	2.27	0.18	1.62	0.26
Arrow F (diagonal)	1.83	0.27	1.83	0.45
Target 3 (remelted)				
Arrow D (transversal)	2.93	0.34	3.83	0.34
Arrow A (diagonal)	2.63	0.31	3.45	0.52
Target 4				
Arrow B (transversal)	2.76	0.4	3.91	0.71
Arrow E (diagonal)	2.14	0.21	3.42	0.37

In all series of shots the transversally hafted arrow had the larger TCSA value. In all cases, the transversally hafted arrow penetrated more deeply than the diagonally hafted arrow (Fig. 8, see appendix).

4.4. Statistical analysis

Because of the small size of the targets, our datasets for direct comparisons are small, with series of 6 or 7 shots of each type into the same target. Some clear patterns can be observed, especially in penetration depth. To further analyze our results, we conducted statistical tests using PAST version 4.17 (Hammer et al., 2001).

First, we test if the difference in penetration depth between arrow types is significant. To do this, we pooled all the series and compared the penetration depth between transversally and diagonally hafted arrows across all series (Table 5). We performed a Shapiro-Wilk test for normality of the pooled data, which shows that the penetration depth of all the series combined is not normally distributed (p diagonally hafted arrows: 0.03; p transversally hafted arrows: 0.03). We then compared the data using a Mann-Whitney *U* test (Table 6), which shows that the

Table 5
Summary of pooled dataset.

Penetration	N	Median	25 %/75 %	Mean	St. dev.
Transversal	23	24.8	18.5/28.4	24.3	1
Diagonal	23	17.2	13.6/20.4	16.6	0.8

Table 6
Results of the Mann-Whitney test.

Mann-Whitney test	Rank	U-value	P(equal)
Transversal/Diagonal	7.5/16	67.5	<0.01

difference in penetration is highly significant ($p < 0.01$).

TCSA values are expected to be inversely related to penetration depth (Hughes 1998; Sisk & Shea, 2011; also see Sitton et al. 2020, 2023). In our experiments this relationship is not apparent. There is a statistically significant positive correlation between lithic TCSA and penetration depth, within each hafting configuration, but also for all shots pooled (Table 7).

5. Discussion

5.1. Hafting configuration and penetrative power

Previous work on projectile penetration has established an important role for the shape of the tip. The tip creates the hole for the shaft to enter. Following Hughes (1998), penetration is a function of mass, velocity and tip shape. Friis-Hansen (1990) emphasises “cutting power” created by a sharply angled point is key. Sisk and Shea (2011) summarize: “the larger the TCSA, the more force is needed.”.

Experimental evidence on the relation between point size as expressed in TCSA/TCSP and penetrative power is more ambiguous. Some studies find that these measurements do relate to penetration, with smaller values resulting in better penetration (e.g. Sitton et al 2020), but other studies report no effect (e.g. Grady and Churchill 2023). Finally, the accuracy with which TCSA/TCSP measures capture the relevant information on point size is contested based on comparisons with TCSA/TCSP values derived from photogrammetry of projectiles (Pettigrew et al. 2023). Other factors may be more relevant in explaining penetration (Clarkson 2016).

Our experimental design keeps kinetic energy (mass and velocity) constant as much as possible. Mass by using uniform shafts and replicated lithics with as similar dimensions as was possible to achieve. Velocity by ensuring the same draw length of the bow for each shot and ensuring the distance between bow and target was the same for all shots. By producing series of shots with both hafting configurations in the same, homogeneous gelatin targets, we keep drag constant too. Our results therefore reveal differences in performance between arrows hafted with typologically similar stone tools but attached to the shaft in differing configurations.

In our experiments transversally hafted arrows consistently penetrate the gelatin blocks better than diagonally hafted arrows. As we have attempted to keep velocity constant and projectile weights are very similar, this suggests that the tip and hafting configurations explain the difference. The TCSA values of the lithics alone have been argued to not be a good predictor of penetration. Calculating TCSA using the thickness of the joint between point and haft may be a better predictor of penetration depth, yet other factors such as kinetic energy and velocity appear more important in explaining penetration (e.g. Pettigrew et al. 2023). As illustrated in Fig. 9, TCSA values of the transversal arrows, with thickness taken at the joint are larger than that of diagonal arrows, yet the transversal arrows consistently penetrate better. Hafting configuration thus predicts penetration better than TCSA. The ranges of variation at one standard deviation do not overlap. Variation in the thickness of the gelatin block at the point of impact does not explain the difference as for targets 2 and 4, the thickness at point of impact was slightly larger for the transversal shots than for the diagonal shots, while in target 1 the diagonal shots on average hit the target at locations of a slightly larger thickness (Table 2). The change in relative performance of arrows A and D across targets 1 and 3 is notable. In target 3, the transversal shots (arrow D) still penetrate more deeply on average than the diagonal shots (arrow A), yet the differences are smaller in magnitude than in target 1. A partial explanation may be formed by differences in the thickness of the target at the point of impact. The average thickness for the series in target 3 is the same, while in target 1, Arrow A hit the target at an average thickness of 11.2 cm and Arrow D at 10.7 cm, meaning the diagonal shots faced on average 0.3 cm larger travel distances through the gelatin, increasing the amount of drag faced. Similar results have been reported by Goldstein and Shaffer (2017) and Yaroshevich et al. (2010), but their experiments were primarily geared to testing other variables. Moreover, their ranges of variation are not reported, making it difficult to evaluate the significance of their results.

Table 7
Correlation coefficients of TCSA and penetration depth. *As hafted TCSA could not be calculated for arrow F, this category has 6 less data points.

	n	r	p
All shots	50	0.39	<0.01
Transversal, lithic TCSA	25	0.72	<0.01
Diagonal (hafted TCSA)	19*	0.59	<0.01

In contrast, the patterning in entry wound size is unclear, neither hafting configuration consistently produces larger wounds than the other and the ranges of variation overlap. Friis-Hansen (1990, 502) discusses Mesolithic transversal arrows and observes that such tips cut a large hole, freeing the length of the shaft of friction in contrast to other hafting configurations where there is more contact (and hence friction) between prey tissue and shaft.

Our TCSA data does not account for much of the variation in penetrative power when TCSA is calculated in the hafted configuration. The smaller the TCSA, the better arrows are expected to penetrate (e.g., Hughes, 1998; Sisk & Shea, 2011). This does not hold in our experiments, where TCSA appears is positively correlated with penetration depth. More importantly, it appears that the hafting configuration is more important in determining penetration depth than TCSA. This is illustrated by the fact that across all the series of shots, the transversal arrow penetrated better than the diagonally hafted arrow. As the relationship between TCSA and penetration depth was not the primary objective of these experiments, more data are needed to make definitive statements. Further experiments to clarify this are currently being planned. Provisionally at least we conclude that hafting configuration is a better predictor at penetrative power than TCSA.

We propose the transversal hafting configuration indeed minimizes the amount of friction experienced by the shaft from the gelatin target (Friis-Hansen, 1990, 502). In formal terms, in the equation proposed by Hughes (1998): Penetration = MV_0/CA, where M and V_0 are kept constant as much as possible, C, the dimensional constant capturing the influence of the projectile shape influences penetration much more than A (TCSA).

5.2. Archaeological relevance

Functional studies have been interpreted to suggest that Howiesons Poort quartz segments likely functioned as projectile points (Lombard, 2011; Lombard & Pargeter, 2008; Lombard & Phillipson, 2010). The configuration in which segments were used is unclear; use-trace evidence has been interpreted to suggest that segments may have been transversally and diagonally hafted, while other studies also leave open their use as barbs (e.g. de la Peña et al., 2018; Lombard, 2008; Lombard & Pargeter, 2008).

However, the use of bow and arrow in the Howiesons Poort has been contested, as have the specific hafting interpretations (e.g., Villa & Soriano, 2010; Villa et al., 2012). This experiment suggests that transversally hafted segments have better penetrative capabilities than diagonally hafted segments. Hafting of such segments as projectile tips is a functionally feasible interpretation (Goldstein and Shaffer, 2017; Lombard & Pargeter, 2008; Pargeter, 2007; Yaroshevich et al. 2010). We add clear insights into the relative penetration in a homogeneous medium. Typologically similar artefacts have been found in many other Stone Age cultures, and these tools are often interpreted as potential arrowheads. Hence, our results have wider relevance for our understanding of prehistoric toolkits than only the Howiesons Poort.

The functional interpretations of these tool-types are often based on the presence or absence of so-called “diagnostic impact fractures”. Nevertheless, such fractures can be caused by other processes, such as knapping and trampling, if in differing frequencies from those expected for projectile use (Pargeter, 2011, 2013; Pargeter & Bradfield, 2012). The study of micro-traces (residues and wear) adds an important dimension to the functional interpretations of backed tool specifically and potential projectiles more generally. Residues may be informative on hafting configurations and worked materials (e.g. Lombard, 2011; Lombard & Pargeter, 2008; Lombard & Phillipson, 2010). Use-wear study also yields data on hafting and on the type of impact undergone by the artefact, but no specific traces can be considered diagnostic of arrow use alone. The interpretation of fracture and wear patterns on quartz is complicated by the material properties of the material (Taipale & Rots 2019) and care should be taken with the results of analyses that do not explicitly take this into account.

Uluzzian lunates for example have been suggested to function as either diagonally or transversally hafted arrowheads based on the frequency of so-called DIF’s (Sano et al., 2019). Segments are often assumed to have functioned as barbs (Chesnaux, 2009; Deacon, 1978; Deeben & Niekus, 2016). Our results show that lunates can feasibly function as arrow-tips.

5.3. *Implications for foraging strategies*

To successfully hunt large game animals, it is generally assumed that a large, deep wound must be created to seriously injure the prey animal swiftly. Thus, a wide arrow with a large perimeter of ~ 2.5 cm is required to inflict rapidly fatal wounds (Friis-Hansen, 1990, 497). Our calculated TCSP values are slightly below that (Table 1). This suggests that the quartz segments were better suited for relatively small-bodied prey. At some sites, the Howiesons Poort period is associated with smaller prey animals than preceding and succeeding assemblages (e.g., Clark, 2011; Dusseldorp, 2014), but this pattern is not universal.

Pettigrew et al. (2023) suggest that TCSA and TCSP may be a good predictor of entry wound size, yet the size of projectiles is imperfectly captured by these formulas and caution is warranted. Moreover, kinetic energy and velocity of the projectile appear more influential, and kinetic energy appears the best predictor of penetration in other experiments (Pettigrew et al. 2023, 22; also see Schoville et a. 2017, 313–314). Ethnographic data on arrow weights is rare, but suggests our arrows are at and slightly beyond the upper end of the range of reported variation (ethnographic range: 13–31,5 g; our arrows 27.6–32.8 g) (Tomka, 2013). This means that hunting larger prey than indicated by TCSA/TCSP calculations is not *a priori* excluded for Howiesons Poort fragments, but the kinetic energy of actual Howiesons Poort projectiles is in all likelihood overestimated by our quite heavy projectiles.

However, the arrows may not have been used to kill prey animals instantly. Injured prey may have been tracked by the foraging party. Further, the killing power may not have been limited to causing organ damage and blood loss. Hafted transversally, the TCSA values for the quartz segments conform to those of ethnographically known “normal” arrows, yet when hafted longitudinally, the TCSA values for quartz segments overlap with poisoned arrows (which generally have smaller tips than non-poisoned arrows) (Lombard, 2020). With the application of poison, much smaller wounds will suffice to exploit prey animals.

Our experiment shows that hafting configuration is a better predictor of penetration than TCSA values. The connection between TCSA/TCSP and preferred prey size therefore should be regarded with caution. Moreover, classifications of weapon type based on point TCSA only may not provide a reliable indicator as hafting technique influences joint thickness, which provides are more reliable TCSA than calculating it based on lithic thickness only (Pettigrew et al. 2023). Under our experimental conditions transversal hafting represents an efficient configuration to produce wounds, yet this does not definitively exclude the use of poison by Howiesons Poort foragers even if the TCSA value is outside that of ethnographically documented poisoned arrows.

6. Limitations

6.1. *Experimental set-up*

Our experiment is designed to test the difference in performance of one variable, the hafting configuration. Hence, the experimental set-up does not mimic real-life conditions. Previous experiments were often set up to produce use-traces as comparative data to interpret archaeological artefacts and so have often used animal carcasses. During such experiments, arrows frequently incur damage due to impact with hide and especially bone. Further, arrows frequently ricochet (e.g. Goldstein & Shaffer, 2017; Lombard & Pargeter 2008; Pargeter 2007; Schoville et al. 2017; Yaroshevich et al. 2010). As we wanted to test the penetrative power of different hafting configurations across multiple shots, we used a homogenous target to avoid the damage arrows can incur inherent to shooting them at carcasses with hide and bone. The targets we used also had a lower consistency than the ballistics gel. This eliminated rebounding arrows, which made the experiments safer and allowed us to produce series of shots with minimal risk of the lithic point breaking.

However, this set-up also brings limitations: Skin appears more difficult to penetrate than muscle tissue (Hughes, 1998, 350). Here the cutting power of an arrowhead (sensu Friis-Hansen, 1990) may be more influential than the arrowhead’s function in reducing drag on the shaft. Pettigrew and colleagues (2023) partially overcame this limitation in their study using actual carcasses. They re-use shafts with different points, when they broke on impact and they present a penetration depth data-set of 12 arrow and 72 atlatl shots. Their work does not include backed segments and the variability in arrow dimensions is substantial, yet their set-up provides a model for future work planned to include hide, or a medium mimicking it to see how this modulates the performance of the different hafting configurations. Schoville et al. (2017) observed that although diagonally hafted segments have shallower penetration than transversally hafted segments in ballistics gel, the diagonally hafted segments ricochet less frequently when shot at a springbok carcass.

We replicated our arrows using shafts of standardized dimensions and we shot them using a commercially available bow. Howiesons Poort tips may have been hafted onto different arrow types (e.g., with thinner shafts) and shot with bows with a different performance. The 8 mm dimension of the shaft appears not unreasonable in view of the shafts of arrows from the ethnographically studied San foragers in Southern Africa. Their arrows appear to have shafts of around 9 mm diameter (Clark, 1975). Ethnographically known San bows are small and their pull is low compared to western bows. One published estimate is 20 lbs. (Clark, 1975). As 60.000 years separate the ethnographic data from the Howiesons Poort, modern San ethnography may not have any privileged relevance to the interpretation of Middle Stone Age archaeological materials. Much heavier bows have been reported from other African contexts. The Hadza for example are reported to use bows with a draw weight of 69.4 lbs. (Schoville et al. 2017). Further, recurve bows have been observed in San rock art in the Western Cape (Manhire et al., 1985). This illustrates the variability in design within the same weapon type. Especially with bows with a low draw weight, small differences in the efficacy of different hafting configurations increase in relevance. There is more of a premium on finding the “optimal” hafting configuration in such contexts.

6.2. *Archaeological interpretation*

Our experiments do not prove that all backed segments functioned as transversally hafted arrows, merely that such an interpretation makes functional sense. We have replicated the average dimensions of quartz segments from a representative Howiesons Poort assemblage (Lombard 2020). However, there is much raw material-related variability in size and shape of segments during the Howiesons Poort. For Sibhudu it was proposed that larger segments in dolerite and hornfels functioned differently and were hafted in different configurations than the quartz segments (Wadley & Mohapi 2008, 263). At Diepkloof, use-trace evidence similarly suggests not all backed pieces functioned identically, with a mix of evidence for domestic activities and projectile use (Igreja and Porraz 2013, 3486).

Also, even if segments were connected to use in bow and arrow technology, this does not automatically imply that they are transversally hafted. For example, use trace analysis has been used to suggest that some segments were perhaps hafted diagonally (Goldstein & Shaffer, 2017; Lombard, 2011; Sano et al., 2019). Further, experiments show that arrows barbed with segments can and do penetrate carcasses, although no clear data on the relative efficacy of penetration in such a configuration is known to us (Chesnaux, 2009). Hence, our experiments render the interpretation of backed segments as transversal arrowheads plausible, but this must ideally be accompanied by additional argument. The experiments reported by de la Peña and colleagues (2018) provide a valuable tool to further explore the versatility of lithic pieces associated with projectiles.

The Holocene segments from Southern Africa’s Wilton technocomplex provide a case in point. Often assumed to function as arrowheads, use-wear evidence on Wilton industry segments yielded evidence for working plant material (Wadley & Binneman, 1995). Nevertheless, there is supporting evidence to interpret at least some of these segments as arrowheads as depictions from the rock art of the Limpopo province and Zimbabwe depict San people with bows and arrows that appear to be hafted transversally. Laue (2000) argues that these represent Wilton-type segments.

7. Conclusion

We have conducted a series of shooting experiments comparing the penetrative power of replicated arrows tipped with Howiesons Poort backed segments in two hafting configurations: transversally tipped arrows and diagonally tipped arrows. Our experiments demonstrate:

- That transversally hafted arrows penetrate much deeper through gelatin targets than diagonally hafted arrows. We propose, following Friis-Hansen (1990) that the transversal tip cuts a path through the target reducing drag on the surface of the shaft more than diagonally hafted tips do.
- That there is no clear pattern in the size of wounds in the targets created by both hafting configurations.
- That hafting configuration of the arrows predicts the penetrative power of the arrows much better than TCSA values.

Calculating the proper TCSA value depends on backed pieces’ hafting configuration. In archaeological contexts, the exact hafting configuration of a lithic piece cannot always be reconstructed because different hafting configurations may produce similar functional traces (see e.g. Lombard 2008, 35), making determination of TCSA values problematic. Further, it appears that TCSA values do not capture fully the relevant characteristics that influence penetrative performance of arrows. Further experimental and ethnographic research to strengthen interpretative frameworks for weapon points thus appears a productive endeavor.

CRediT authorship contribution statement

Gerrit L. Dusseldorp: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mick van Harderwijk:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Morgan Roussel:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Alessandro Aleo:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105365.

Data availability

The data used in the paper is presented in the manuscript and the supplementary material.

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