The effect of edge serration on the performance of stone-tip projectiles: an experimental case study of the Maros Point from Holocene South Sulawesi

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Abstract
Serrated stone points have been documented in a variety of archaeological settings worldwide. In Indonesia, serrated points known as Maros point began to appear during the mid-Holocene as part of the Toalean techno-complex in southern South Sulawesi. Researchers have speculated functional and cultural reason behind the emergence of these distinctive artefact as projectile points, an assumption that has yet to be verified by archaeological data. In particular, the edge serration has been suggested to allow for deeper penetration and/or act as barbs to prevent the easy withdrawal of the points from the target. In this study, we experimentally test these functional hypotheses regarding the effect of edge serration on stone arrowheads resembling Maros points when fired using different bow draw weights. We also investigate variation in breakage and impact fracture pattern between serrated and non-serrated points. Our result show that, compared to the non-serrated points, the serrated arrows not only deliver deeper penetrations, but also require less force to withdraw from the ballistic gel target. However, these relationships are complicated by the inclusion of skin and bone in the ballistic target. The findings demonstrate that the effect of serrated stone points on projectile performance depends on factors such as the projectile delivery system and prey type. Moreover, under identical firing settings, the serrated points develop more variable macrofracture patterns than the non-serrated points, likely owing the irregular edge morphologies. Taking these results together, we discuss the implications of our experimental study on the appearance of Maros points and the Toalean techno-complex in South Sulawesi during the mid-Holocene.

Keywords Projectile point · Serration · Maros point · Experimental archaeology

Introduction

Among the wide variety of stone points documented in the global archaeological record, there exist a number of point types that feature tooth-like serration along the edge margins. These serrated points display considerable variation in their morphology and occur across diverse temporal and geographic context (Rots et al. 2017; Smallwood et al. 2018). With the general assumption that these points were hafted as either knives or projectile tips, hypotheses about the purpose of the serration have involved functional and socio-cultural factors. Yet, very few experimental studies to date have explicitly examined these hypotheses, especially under controlled conditions (Loendorf et al. 2015, 2017). As such, the reasons for why past toolmakers in disparate settings converged on application of edge serration on stone points remain poorly understood.
In Southeast Asia, the Maros point represents a unique serrated point type associated with the mid-Holocene Toalean techno-complex in southern South Sulawesi approximately 8–3.5 ka. (van Heekeren 1972; Glover and Presland 1985; Bulbeck 2004; Bulbeck et al. 2000; Bellwood 2007; Suryatman et al. 2019; Perston et al. 2021a, 2021b). Generally described as small retouch points that are roughly triangular or ovate in plain view, the Maros point is mainly characterised by their concave/indented base and serrated margins made up by a series of notches along the edges (Fig. 1; Perston et al. 2021b; Bulbeck et al. 2000; van Heekeren 1957; Mulvaney and Soejono 1971; Bulbeck 2018). The depth of these notches forming the serration can range from shallow to deep (Perston et al. 2021b). Because of the point-like morphology, these artefacts were early described as ‘arrowheads’ (Sarasin and Sarasin 1905). While later studies have been more conservative in relating the Maros point to specific projectile systems (Heekeren 1972), there remains a common assumption that Maros points were associated with projectile armature (Bellwood 2007; Hakim et al. 2019; see Perston et al. 2021a). A similar assumption of projectile and composite technology has also been made about other Toalean artefacts types, including backed artefacts, sawlettes, bone points and other forms of retouched stone tools, and the technological and functional reason behind the production of the serration remain unclear. While there are example retouched point types in the region (Forestier 2007; Forestier et al. 2017; Perston et al. 2021b), there are no other examples with edge serration. The geographically closest example of stone points with similar serrated retouch is the Kimberley point of north-western Australia. Produced from around 1.4–1 ka until the recent past (Maloney et al. 2014; Harrison 2004), these points bear distinctive bifacial retouch and edge serration finely made by pressure flaking (Moore 2015). Ethnographic records indicate that Kimberley points were manufactured from stone or glass as spearheads for fighting, hunting and trade purposes (Harrison 2004; Akerman et al. 2002). Based on the superficial resemblance between Kimberley points and Maros points, researchers have speculated cultural connections between South Sulawesi and Australia during the Holocene (Olsen and Glover 2004). However, compared to Maros points, Kimberley points tend to have a rounded base and an overall

According to this definition, the retouch of the Maros point can either be unifacial or bifacial on at least one of the two margins, and the retouched edge can be steep but not abrupt enough to resemble backing. Perston et al. (2021b) also defined the Mallindrung points, which are serrated points like the Maros point but lack the concave indented base. There also exist non-serrated points in the Toalean including the Lompoa point that has a concave base similar to the Maros points, and the Pangkep point that does not have a concave base. It remains unclear if these non-serrated points represent unfinished preforms or end-product types distinct from the serrated points.

As mentioned already, the Toalean stone points are commonly assumed to represent projectile tips, specifically arrowheads (Bulbeck et al. 2000). It is important to point out that this assertion remains a hypothesis that has yet to be tested on archaeological data through use-wear analysis (Maloney et al. 2022). Yet it is important to note that painted rock art in the region does depict hunting scenes involving the probable use of projectile technologies like spear thrower as well as bow and arrow (Aubert et al. 2018; Leihitu and Permana 2018). Thus, the scenario that these retouched points served as the tips of projectile weaponry in the past is plausible. Importantly, the serrated margins of the Maros Point (as well as the Mallindrung point as per Perston et al. (2021b)) are unique among Southeast Asian stone tools, and the technological and functional reason behind the production of the serration remain unclear. While there are example retouched point types in the region (Forestier 2007; Forestier et al. 2017; Perston et al. 2021b), there are no other examples with edge serration. The geographically closest example of stone points with similar serrated retouch is the Kimberley point of north-western Australia. Produced from around 1.4–1 ka until the recent past (Maloney et al. 2014; Harrison 2004), these points bear distinctive bifacial retouch and edge serration finely made by pressure flaking (Moore 2015). Ethnographic records indicate that Kimberley points were manufactured from stone or glass as spearheads for fighting, hunting and trade purposes (Harrison 2004; Akerman et al. 2002). Based on the superficial resemblance between Kimberley points and Maros points, researchers have speculated cultural connections between South Sulawesi and Australia during the Holocene (Olsen and Glover 2004). However, compared to Maros points, Kimberley points tend to have a rounded base and an overall

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**Fig. 1** Examples of Maros point from excavation at Cappalombo 1 (A, B), Leang Jarie (C) and Leang Paningge (D) in South Sulawesi
shape that varies from ovate to lanceolate instead of triangular (Akerman and Bindon 1995).

For other instances of serrated stone points, one has to look elsewhere in the world. One example is the serrated bifacial points found before or during the Still Bay technocomplex around 77 ka in Southern Africa, at sites such as Sibudu and Umhlutuzana Rock Shelter (Rots et al. 2017). There is notable variation in the morphology of these Middle Stone Age serrated points. At Umhlutuzana, Lombard et al. (2010; also see Mohapi 2013) noted that the serrated points are relatively long and narrow, with a blade-like morphology that is similar to the non-serrated Still Bay points. At Sibudu, however, Rots et al. (2017) described the points to have a general triangular shape with variable size and cross-sectional forms. These variations were attributed to the alternation of serration notching and the influence of raw material. There are also notable differences in the size and placement of the serration, as well as the way the notches were made (bifacial versus unifacial). Based on wear and residue, these serrated points likely functioned as tips of hunting projectiles (Rots et al. 2017; Lombard 2005; Lombard et al. 2010). Several examples of serrated stone points have also been described in North America. The Late Paleoindian Dalton point is a lanceolate point with a concave base that occasionally possesses serration on the lateral margins, though the size and placement of the serration can vary (Smallwood et al. 2020). Other serrated point types include the Stockton type points in California (Hester and Heizer 1973), the serrated points associated with the Hohokam culture in southern Arizona (Loendorf 2013), the stemmed Scallorn points of the Late Woodland period (Smallwood et al. 2018; Patterson 1996) and the Early Archaic Taylor points of the East Woodland (White 2019). Again, these point types vary considerably in their size, overall shape (lanceolate vs. triangular), base (concave vs. stemmed) and edge modification (serration vs. denticulation).

The above examples demonstrate that, beyond the Maros points of Indonesia, there is considerable geographic and temporal variation in the occurrence and morphology of serrated stone points. Assuming that these points were primarily used as projectile points, some aspects of the morphological differences, such as point size and cross-sectional profile, may be associated with functional factors related to projectile aerodynamics and the delivery system (Christenson 1986; Sitton et al. 2020; Hughes 1998; Eren et al. 2022; Sisk and Shea 2011). In North America, it has been suggested that the point cross-section area correlates with the weapon delivery system, with spear points having the largest cross-sectional area, followed by thrown darts and then arrow heads (Shea 2006). Thus, the emergence of small, thin, triangular points in North America has been attributed to the adoption of bow technology (Blitz and Porth 2013; Hughes 1998). In this vein, the small and thin profile and the triangular form of the Maros points may support the possibility that these serrated points may support the possibility that these serrated points functioned as arrowheads rather than tips of thrown darts. However, the identification of weapon velocity and projection system among archaeological stone points remains a contentious matter (Hutchings 2016; Newman and Moore 2013), and further studies are needed to clarify the delivery system associated with the Maros points of Sulawesi through multiple lines of evidence (Coppe et al. 2022; Maloney et al. 2022).

**Why serrate?**

Rots et al. (2017) noted that most of the serrated point types around the world seem to be restricted in time and space. The lack of a more widespread, consistent uptake of serration among stone points suggests that the trait does not offer universal advantage to the performance of stone-tip projectiles. Instead, researchers have proposed culturally specific factors to explain the manifestation of serrated points, including for ceremonial use, trade, social signalling and prestige (Johnson 1940; Akerman and Bindon 1995; Loendorf et al. 2015; Maloney 2020). For instance, Hoffman (1997) and Loendorf et al. (2015, 2017) suggested that the serration on the blade margins of some Hohokam projectile points in southern Arizona was to intentionally signal group affiliations. Similarly, variation in the production of Kimberley points in Australia has been discussed in terms of the negotiation and maintenance of identity and social relations, as well as the expression of skill and social prestige (Högberg and Lombard 2020; Moore 2011; 2015; Maloney 2020).

However, there is arguably a degree of consistency in the design of serration among projectile points that cross-cut cultural context. In their study, Smallwood et al. (2018) used geometric morphometric analysis to compare the serration among Dalton and Scallorn points from North American and Kimberley points from Australia. The results show that there is no significant difference in the serration among these distinct point types, implying the possibility that the edge modification was designed for similar functional purposes. From this view, the lack of a ‘selective sweep’ in the uptake of serration among stone points may be because the functional advantage associated with edge serration depends on the context of use, such as the type of prey hunted, the projecting system and the shooting distance. Several hypotheses have been proposed for the functional advantage of projectile edge serration. Some suggest that serration increases the cutting ability of a knife edge, as the high points on a serrated edge allow force to be concentrated during cutting for easier penetration (Frazzetta 1988). Thus, it may be that serrated edge margins on projectile points cause deeper penetration in targets (Ellis 1997). Serration has also been said to produce larger wounds as the edge tears instead of slices.
through the internal tissues (Frazetta 1988; Abler 1992; Hughes 1998; Rots et al. 2017). As noted by Smallwood et al. (2018), this latter view is supported by forensic studies showing that serrated knives create significantly different wounds to those produced by non-serrated knives, including striation marks on the skin, cartilage and other soft tissues (Pounder et al. 2011; Thompson and Inglis 2009), which would result in greater damage and bleeding in the target prey. Similarly, some have argued that the serrated margins may function like ‘barbs’ to prevent the easy withdrawal of the point from the wound (Johnson 1940; Hughes 1998; Sliva 2015), allowing the projectile to cause more damage and bleeding as the animals flee (Catlin 1975; Flenniken and Wilke 2016; Cundy 1989). From this perspective, the serrated margins of the Maros point may reflect a specific functional design to enhance the tool’s performance as a projectile point.

Few experiments to date have explicitly tested the functional performance of serrated versus non-serrated stone points in projectile delivery. Loendorf et al. (2015, 2017) conducted two controlled experiments examining the effect of edge serration on the performance of arrowheads. By firing arrows hafted with either serrated or non-serrated triangular obsidian arrowheads from a fixed recurve bow and a constant draw weight, the authors showed that there is no clear difference in accuracy, penetration depth and durability between the two arrowhead types. Based on these results, Loendorf et al. (2015, 2017) concluded that edge serration does not affect the performance of arrowheads. The controlled design and repeated replication employed by Loendorf et al. (2015, 2017) means that their experimental results are internally consistent under the tested conditions and are unlikely to be confounded by other variables (Lin et al. 2018; Eren et al. 2016). However, their negative finding regarding the effect of edge serration is surprising as it goes against the range of functional and ethnographic claims that serration points lead to greater penetration and/or damage. A possible explanation for this discrepancy is that the effect of edge serration is contingent on other factors involved in the projectile delivery process. One possible parameter that influences the performance of serrated projectile points is velocity (Lepers and Rots 2020). From an aerodynamic perspective, protrusions on the edge margin of projectiles like serration increases surface roughness, causing greater pressure drag during flight (Hughes 1998). By extension, edge serration would also increase penetration resistance upon contact with the target. As a result, Hughes (1998) suggested that points with serrations or barbs should be associated with greater projecting velocity in order to offset the increased resistance. From this view, it stands to reason that the performance of serrated points as projectile tips may vary depending on the projecting velocity, such that a certain threshold of velocity is required before the edge serrations can be pushed into the target to cause deeper or greater damage. Returning to the experiments by Loendorf et al. (2015, 2017), the authors controlled projectile velocity by using a recurve bow of a 14-kg draw weight and a 47-cm draw length for all of the tested arrows. Given that the draw weight of a bow is usually measured at a draw length of 28 in. (or 71 cm), the actual draw weight used by Loendorf et al. (2015, 2017) to propel the arrows was likely lower than 14 kg. In comparison, although highly variable, ethnographic records of bow draw weight show average values between 30 and 50 lbs (14 to 23 kg) at normal draw (Cattelain 1997). There are also examples of bows with exceptionally high draw weight. For instance, the Hadza of Tanzania uses bows with a draw weight that can reach up to 100 lb (45 kg) (Roth 2004), while the New Guinea hunting bow is estimated to have a 80–90 lbs draw weight (36–41 kg) (Cattelain 1997). Archaeologically, the draw weights of Neolithic bow have been estimated to between 24 and 84 lbs, which are in line with the ethnographic range (Junkmanns 2013; Coppe et al. 2022).

Given that many of the ethnographically documented bows have a draw weight that exceeds the range used by Loendorf et al. (2015, 2017), it remains to be investigated whether the lack of difference in the performance of serrated and non-serrated points, as observed by Loendorf et al. (2015, 2017), extends to settings of higher bow draw weight and velocity. Another aspect about the functional effect of serration points that has yet to be investigated experimentally is the hypothesis that edge serration acts as barbs (Johnson 1940; Hughes 1998; Sliva 2015). If this were the case, we would expect serrated points to require more force to be removed from the target than non-serrated points. This ‘barb-like’ effect may be further compounded by the presence of bone and hide in the target as these structures can be caught by the serrated edge, further preventing the withdrawal of the point. While Loendorf et al. (2015, 2017) did include inelastic material like rawhide and polymethylmethacrylate on some of the targets used, the authors did not examine the force required to withdraw the arrows from the target.

In this study, we examine these functional hypotheses concerning the effect of edge serration with specific reference to the Maros points of Indonesia, specifically if the Maros points did function as arrowheads. We hypothesise that the serrated margin does cause the arrows to penetrate deeper into the target than non-serrated arrows when the projectile speed increases through the use of a higher bow draw weight, and withdrawing a serrated Maros point arrow requires more force than that for a non-serrated arrow, and this difference in withdrawal force increases with the presence of bone and hide in the target. To test these hypotheses, we conducted a controlled ballistic experiment using a setup similar to that of Loendorf et al. (2015, 2017) to fire arrows hafted with triangular bifacially retouched arrowheads, half...
serrated to resemble the Maros points and half left unserrated. The arrows were shot using bows of two different draw weights at targets of varying structural complexity composed of ballistic gel, pig rib bone and/or fresh pig skin. We further examined breakage rates and use-wear of the experimental arrowheads to see if the serrated and the non-serrated points differ in their durability and macrofracture pattern associated with projectile impact. In particular, we assess whether the serrated margins complicated the formation of impact fractures typically used as diagnostic markers for projectile impact and use. The experimental use-wear data are important for providing a set of reference for future traceology studies of archaeological Maros points.

**Material and methods**

**Experimental design**

A total of 72 arrowheads were made from Texas chert by using a hammer stone and an antler bopper, and finished with a copper-tipped pressure flaker. Half of the arrowheads (n = 36) were left unserrated while the other half were further retouched to produce serration on the two edges that form the point (Fig. 2). The serration was done by making small notches evenly spread out along the entire edge on both margins of the points. The size and shape of the arrowheads and the serration were made to align with the range of variation represented among archaeological Maros point specimens recovered from multiple Toalean sites (Table 1). The size of the experimental serrated and non-serrated points share no statistical difference in length (Mann–Whitney U test: U = 699, p = 0.43), width (Mann–Whitney U test: U = 679.5, p = 0.57), thickness (Mann–Whitney U test: U = 726, p = 0.27) and tip cross-sectional area (Mann–Whitney U test: U = 720, p = 0.30). All of the arrowheads were hafted to the end of standardised pine arrow shafts (8 mm in diameter and 32 inch long with a spine of 35–45 lb) with industrial epoxy (Fig. 2). The arrows were fired using an Apex Hunting R2 Podium Recurve Bow fitted with 38 lbs Black Sheep Apollo limbs, mounted to a platform secured to the ground in order to prevent any movement during firing. During the experiment, the bow string was drawn and locked at a set draw length and released via a mechanical trigger device (Fig. 2). This controlled experimental design minimises the influence of human variation on key parameters (e.g. shooting position and angle, draw length) that can confound the experimental result (Iovita et al. 2014; Perston et al. 2021b), Leang Bulu’ Sipong 1 (n = 26; Perston et al. 2021b), Leang Pajae (n = 9; Perston et al. 2021b) and Leang Rakkeoe (n = 3; Perston et al. 2021b). The data on archaeological serration notch size are based on Maros points recovered from the site of Leang Panninge (n = 102; Anshari 2018)

|                           | Length (mm) | Width (mm) | Thickness (mm) | Tip cross-sectional area (mm²) | Serration notch width (mm) | Serration notch depth (mm) |
|---------------------------|-------------|------------|----------------|-------------------------------|---------------------------|---------------------------|
| Archaeological reference  | 23.4 (10.8–35.0) | 13.2 (7.3–20.7) | 3.2 (1.5–7.2) | 22.8 (8.4–74.3) | 2.6 (0.85–4.93) | 1.8 (1.0–4.0) |
| Experimental serrated (n = 36) | 26.4 (22.2–30.6) | 18.5 (13.5–22.9) | 3.9 (2.2–5.6) | 36.8 (18.9–60.7) | 1.9 (1.5–2.4) | 1.4 (1.1–1.9) |
| Experimental non-serrated (n = 36) | 26.0 (22.6–29.9) | 18.1 (14.0–20.8) | 3.7 (2.3–5.8) | 34.52 (17.3–53.8) | NA | NA |
Schoville et al. 2017; Shea et al. 2001). All of the shooting experiments were carried out at the Illawarra Archery Club with appropriate permission and supervision.

Across all firing trials, the ballistic target was positioned 5 m away from the bow. Note that this distance is comparatively shorter than the range documented ethnographically, which has been estimated to between 25 and 30 m for accurate shots (Cattelain 1997). However, the shorter distance employed here allows greater control over accuracy, such that each shot fired can hit the desired area on the ballistic target. Controlling accuracy is important to prevent the arrows from striking a previously hit location on the targets. Between each firing trial, the target was shifted to ensure the arrow makes contact on a fresh target area. Four different target types were used in this study, each with different structural complexity that mimic aspects of the anatomical structure of animal prey. The first target was composed of ballistic gel only (28×18×15 cm), made to a consistency that resembles muscle tissue by using the Fackler and Malinowski recipe (Fackler and Malinowski 1985; Jussila 2004) with 10% gelatin solution/90% water and stored for more than 24 h in a cold chamber before use. This first target was used to gauge the baseline difference in the effect of the two arrowheads when encountering a homogenous muscle-like medium of uniform resistance. The second target was composed of the same ballistic gel but with fresh pig skin covering the outside of the gel target. This target allows us to isolate the effect of animal skin or hide on arrow performance. Pig was chosen for this experiment because the remains of Sulawesi warty pigs (Sus celebensis) are often associated with Toalean artefacts (Clason 1989; Suryatman et al. 2019; Brumm et al. 2018; Saiful and Hakim 2016; Fakhri 2017; Fakhri et al. 2020) and hence represents a possible prey for which Maros points were used to hunt (see Perston et al. 2021a; Maloney et al. 2022). The third target consisted of the ballistic gel with fresh pig rib bones inserted within. Two sets of rib racks were placed inside the gel at 5 cm and 12 cm respectively from the surface of the target to simulate a simplified structure of a rib cage. The fourth target consisted of ballistic gel with the rib bone insert and fresh skin cover, representing the most complex test medium used in this study. By comparing the results across the four targets, it is possible to disentangle the effect of the two arrowhead forms on each of the target components (i.e. gel, ribs, skin).

Two sets of experiments were carried out in this study with the recurve bow mentioned earlier (Table 2). To test the hypothesis that increasing projectile velocity changes the performance of serrated points, the first experiment shot serrated and non-serrated arrows using two different draw weights, 11 kg and 15 kg (measured using a digital weight scale while pulling the bow to a constant draw length of 40 cm and 45 cm respectively). This experiment was carried out using only the ballistic gel target. To further assess the performance of serrated and non-serrated points on more complex targets, the second experiment shot serrated and non-serrated arrows using a constant draw weight of 15 kg (45 cm draw length) at the three targets consisting of varying combinations of gel, fresh hide and bone. Across both sets of experiments, arrows with no visible damage and use-wear after firing were reused in subsequent experiments to maximise the number samples tested. This mainly applied to the arrows fired in the first experiment as the ballistic gel target did not cause any visible damage to the arrowheads. By doing so, a total of 18 serrated and 18 non-serrated arrows were fired in each combination of bow draw weight and target type.

### Data recording

In terms of firing the arrows, a hand-held speed gun (Bushnell model number 101911) was used to monitor the arrow travel speed. The speed gun measures travel speed within the range of 16–177 km per hour (kph) at a distance up to 90 feet with an accuracy of ±1 kph. To ensure accurate measurement, the speed gun was placed in line of the arrow firing direction and activated just before the arrow release. Given the fixed firing position of the bow and constant draw weight, we expect the arrow velocity to be more or less similar across the trials using the same bow.

| Hypotheses tested | Experiment 1 | Experiment 2 |
|-------------------|--------------|--------------|
| • Increasing projectile velocity changes the performance of serrated points | • Arrow penetration depth varies by target composition | • Arrow penetration depth varies by target composition |
| • Serrated points require more force to withdraw | • Arrow withdraw force varies by target composition | • Arrow withdraw force varies by target composition |

| Target type | Gel | Gel | Gel+skin | Gel+bone | Gel+skin+bone |
|-------------|-----|-----|----------|----------|---------------|
| Bow draw weight (draw length) | 11 kg (40 cm) | 15 kg (45 cm) | 15 kg (45 cm) | 15 kg (45 cm) | 15 kg (45 cm) |
| Arrow type | • Serrated | • Serrated | • Serrated | • Serrated | • Serrated |
|               | • Non-serrated | • Non-serrated | • Non-serrated | • Non-serrated | • Non-serrated |
In terms of arrow performance, we recorded the penetration depth of each arrow in the target. This was done by marking the location on the arrow shaft that intersects the surface of the target before pulling the arrow out of the target, then measuring the distance between the marking on the shaft to the tip of the arrow with a digital calliper. We expect that the inclusion of the rib and hide in the target would cause arrow penetration to decrease, as these elements would impede the arrows from travelling farther into the ballistic gel. In particular, with the ribs positioned at a fixed location within some of the targets, we anticipate the arrow penetration depth to be less variable for these targets because the arrows would hit the rib bones instead of penetrating farther into the target. Note that unlike Loendorf et al. (2015, 2018), we did not normalise the penetration depth measurements by arrow weight because there is no systematic difference in the size of the serrated and non-serrated arrowheads used in this study (Table 1).

Another variable measured was the amount of force required to pull out the arrow from the target after firing (hereafter as ‘withdrawal force’). This was measured by a Sauter force gauge (Model FL10), which has a peak hold function that can capture the highest value recorded during measurement up to 11.54 N (or 1.18 kg force). To record withdrawal force, a string loop was secured to the end of each arrow shaft before the experiment. After firing, the force gauge was hooked to a string loop to withdraw the arrow through a single, linear pull motion. If edge serration functions as barbs, we expect an arrow with a serrated arrowhead to require more withdrawal force to be released from the target than an arrow with a non-serrated arrowhead. We also predict that the withdrawal force would be higher when the firing target contains rib bones and/or hide, as the arrow may be caught by these additional elements when exiting the target. Because withdrawal force is correlated with penetration depth (the deeper the penetration the more force required to withdraw the arrow), we standardise the withdrawal force measurements by their associated penetration depth to determine the withdrawal force per 1 cm of penetration depth.

To determine point durability, we differentiate between breakage and macrofracture. The former represents damage to the arrowhead that altered its overall shape to an extent that we think would impact its functional performance, such as major snapping or shattering. Macrofracture, on the other hand, is used to denote small-scale damage and use-wear on the arrowhead after firing. This form of damage includes minor edge scarring and crushing that we think do not hinder the functionality of the arrows. For breakage, arrows were classified as either ‘complete’ or ‘broken’ depending on their state after firing. ‘Complete’ arrowheads were those that remained intact with no visible breakage, but may contain macrofracture; ‘broken’ arrowheads were those that have damage ranging from a broken tip to major shattering. Note that the breakage and macrofracture information were only recorded on arrows that were not reused. To facilitate the analysis of macrofracture, each arrowhead was cleaned in an ultrasonic tank filled with a mild solution of dishwashing liquid and distilled water for 3 min, before being rinsed with distilled water mixed with 70% alcohol and air dried on a paper towel. This cleaning procedure removes any stains on the arrowheads and allows for any polish and striation to be properly observed (Unrath et al., 1986). After cleaning, each arrowhead was analysed using an Olympus SZ stereo microscope (5–45× zoom) and a Dino Lite premier series equipped with a LED ring light illumination unit and a polarizer ring. Images of the analyses were captured using Lumenera Infinity 2 camera and the Infinity Analyze software (version 7). The macrofractures were described in terms of the characteristics and location of the scars associated with projectile point use (Rots and Plisson 2014; Coppe and Rots 2017). Specifically, we report the location of the scar initiation (ventral surface and/or dorsal surface, distal tip of the point and/or the lateral edges), the general direction of the scars (parallel, oblique or perpendicular to the long axis of the point) and termination type (feather, hinge step). We also document any spin-off fractures (a cone fracture that initiates from an earlier fracture surface) and burin-like fractures (a fracture that propagates along a lateral edge) that have been previously to occur on projectile points (Coppe and Rots 2017).

Statistical analyses were conducted using the R statistical software (R Core Team 2021). The non-parametric Mann–Whitney U test was used to compare each arrow type in terms of the penetration depth and withdrawal force under different firing conditions and target settings. A Test of Equal Proportions was used to compare the breakage rate of the two arrow types. An alpha value of 0.05 was used to determine statistical significance.

Results

Arrow performance in ballistic gel under different draw weight

The average arrow travel speed was 130.7 kph (sd = 3.9) when fired under a 11-kg draw weight and 160.5 kph (sd = 3.9) under a 15-kg draw weight. This variation in arrow delivery speed correlates with the overall difference in arrow penetration depth, with the 11-kg draw weight producing an average penetration depth of 11.8 cm (sd = 1.1) and the 15-kg draw weight producing an average penetration of 14.2 cm (sd = 1.2) (Fig. 3). In terms of the effect of edge serration, the serrated arrows penetrated deeper into the ballistic gel target than the non-serrated arrows under
both draw weight settings (11 kg: $W = 38.5$, $p < 0.001$; 15 kg: $W = 93$, $p = 0.03$). However, the actual difference in average penetration depth between the two arrow types is relatively small (1.4 cm under the 11-kg draw weight; 0.8 cm under the 15-kg draw weight).

**Arrow performance by different target type under a constant draw weight**

Overall, the arrow penetration depth decreased as the structural complexity of the target increased (Fig. 4). Compared to the gel-only target (average penetration depth = 14.2 cm), the inclusion of the pig skin saw the overall arrow penetration decreased by an average of 1.1 cm (average penetration depth = 13.1 cm), while adding the rib bones led to a reduction in average arrow penetration by 1.5 cm (average penetration depth = 12.7 cm). For the target that contains the rib bones but not the skin, all of the tested arrows penetrated through the first rib rack and stopped at an average depth around where the second rack is positioned within the target. This pattern suggests that the location of the second rib rack may have had a systematic effect in stopping the arrows from penetrating deeper into the target. Opposite to our prediction, the presence of the rib bones in the target caused the arrow penetration depth to be more variable (sd = 2.1) than those associated with the target without the bone inserts (gel-only: sd = 1.2; gel + skin: sd = 0.8). When the target contains both skin and bone, the arrow penetration depth is on average 4 cm shallower than the penetration depth associated with the gel-only target (average penetration depth = 10.2 cm), and the majority of the arrows did not reach the second set of rib bones. This last and most complex target also produced the greatest amount of variation in penetration depth (sd = 2.6).

Looking at the overall performance of the two arrow types across the targets, the serrated arrows tend to penetrate slightly deeper (average = 13.1 cm) than the non-serrated arrows (average = 12.2 cm) ($W = 1892.5$, $p = 0.007$). However, if we look at the targets individually, the penetration difference between the two arrow types is only statistically significant with the gel-only target (see above for statistical results). No notable difference in the performance of the two arrow types was detected for the other three targets (gel + skin: $U = 112$, $p = 0.07$; gel + bone: $U = 112.5$, $p = 0.19$; gel + skin + bone: $W = 104$, $p = 0.11$).

For arrow withdrawal force, the force required to release some of the tested arrows exceeded the measuring capacity of the force gauge. Based on the values we did manage to measure ($n = 101$), the non-serrated arrows required more force to pull out from the ballistic gel target than the serrated arrow ($W = 245$, $p = 0.008$) (Fig. 5). However, as with penetration depth, this difference in withdrawal force disappeared when skin and bone were added to the target. Interestingly, while the inclusion of either skin or bone did not substantially alter the arrow withdrawal force, the combination of both additional elements in the target led to considerably higher and more variable force values than the range observed among the other experimental settings (Fig. 5). This difference is unlikely to be an outcome of measurement error as other targets were recorded under the same experimental setting. Instead, the cause of this discrepancy is currently unclear.
Breakage and macrofracture

In terms of breakage, all of the arrows fired at the gel-only target displayed no sign of breakage after firing. In comparison, the inclusion of skin or bone in the target led to some damage on the arrowheads (Fig. 6), with the rib bone inserts causing a higher proportion of breakage (6 out of 29, or 17%) than the skin add-on (1 out of 36, or 3%). The damage rate is at the highest when the target contains both skin and bone, with 10 of the 36 tested arrows (28%) showing varying degrees of breakage. Between the two arrow types, while there are proportionally more non-serrated arrows with breakage (17%) than serrated arrows (7%), the difference is not statistically significant ($X^2 = 2.40, df = 1, p = 0.12$). Similarly, no statistical difference in breakage rate was detected between the two arrow types among the individual target types (gel + skin: $X^2 < 0.001, df = 1, p = 1$; gel + bone: $X^2 = 2.02, df = 1, p = 0.15$; gel + skin + bone: $X^2 = 0.14, df = 1, p = 0.71$).

A total of 36 arrowheads exhibit macrofracture after firing, all of which occur on the distal end of the points. The observed macrofractures include macro scaring with varying termination types (feature, hinge, step) (Fig. 7b, d), spin-off scarring along breakage (Fig. 7a) and larger damage at the tip of the point typical of impact fracture (Fig. 7c). No burin-like fractures were observed. Between the two point types, the majority of the non-serrated arrowheads (11 out of 14, or 78%) exhibit macrofracture only at the tip of the point, with scars parallel to the point axis typical of projectile impact fracture. In comparison, the distribution of macrofracture is more variable among the serrated points, with the majority displaying macrofracture scars not only at the tip but also along the adjacent lateral edges (15 out of 22, or 68%; Fig. 7b, d). This more variable scar distribution on the serrated points is likely a result of their irregular edge configuration, which provided more places for scar initiation to occur upon impact. In terms of the surface position of the macro scars, the majority of the arrows have scars on both the ventral and dorsal surfaces (19 out of 36 or 52%), while those with ventral- or dorsal-only scaring are in the minority at equal proportions (5 out of 36 or 13%). Detailed summary description of the observed macrofractures are provided in Table 3 in the Appendix.

Discussion

Serrated margins on stone points such as the Maros point of South Sulawesi have been hypothesised to provide functional benefits to stone-tip projectiles (e.g. Frazzetta 1988; Hughes 1998; Ellis 1997). Yet, previous controlled experiments by Loendorf et al. (2015, 2017) observed no significant difference in the performance of serrated and non-serrated points when fired into ballistic gel targets. In this study, we hypothesised that the effect of edge serration on stone projectile points like the Maros point is conditioned by the projectile delivery speed. By using a bow with a higher draw weight than that employed by Loendorf et al. (2015, 2017), the serrated points in our experiment consistently penetrated deeper into the ballistic gel target than the non-serrated points across the two draw weight levels tested. This finding supports the hypothesis that serrated margins do confer a functional benefit to projectile performance when using a larger bow. It is likely that the larger draw weight allowed the arrows to impact the target with greater speed and energy, allowing the serrated edges to better tear through the target and cause deeper penetration wounds (Frazzetta 1988; Ellis 1997). However, looking across the two draw weight levels tested here, while the overall penetration depth
did increase with a higher draw weight, the penetration difference between the serrated and the non-serrated points did not become greater. One possibility is that the two levels of draw weights tested here are not sufficiently large enough to cause notable changes in the effect of serrated points. Alternatively, the influence of edge serration may operate as a ‘threshold effect’—that it occurs once the levels of certain delivery parameters (e.g. draw weight and projectile velocity) are met, but the strength of the effect itself does not increase subsequently with these parameters.

With increasing structural complexity of the ballistic target in our experiment, the average penetration depth of the serrated arrows was consistently higher than that of the non-serrated arrows, though these average differences were no longer statistically meaningful when the gel target contained additional elements. Instead, the inclusion of skin or bone caused the overall penetration depth of the two arrow types to decrease, reflecting the higher penetration resistance introduced by these components. When both skin and bone were included, we saw the lowest overall penetration depth achieved among all of the targets tested. Contrary to our prediction, however, the addition of the rib bones led to a greater amount of variation in the arrow penetration depth. In hindsight, this makes sense as the rib bone is not a homogenous structure, such that some of the arrows can hit the bone at different locations while others pass through the flesh in between the rib bones. Moreover, the placement of the rib bones in the targets here likely influenced the arrow penetration depths observed. If the second rib rack was placed farther back within the gel targets (which can represent a larger ‘rib cage’), it is possible that the arrows would penetrate even deeper into these targets.

In terms of withdrawal force, our results show that the non-serrated arrows actually required more force to withdraw from the ballistic gel target than the serrated arrows. This finding rejects the hypothesis that edge serration acts as barbs to prevent arrow withdrawal. Instead, the serrated arrows required less withdrawal force, perhaps because the serrated margins tore through the target and produced larger wound tracks that in turn facilitated the release of the arrows. In contrast, wounds caused by non-serrated margins in the ballistic gel could actually ‘close up’ following the passing of the arrowhead in the target, thereby increasing the amount of force required to withdraw the arrow. However, as with penetration depth, this difference in withdrawal force between the two arrow types went away when the skin and bone components were added to the ballistic target. Moreover, the withdrawal force increased considerably when the target contained both the skin and the bone, especially among the non-serrated arrows. This change may reflect the arrows getting caught by the skin and bone elements upon withdrawal. If this was the case, however, it is unclear why we did not observe similar increases in withdrawal force in the other two targets that contain the skin and the bone components separately. As mentioned earlier, the withdrawal force for some of the arrows in our study were beyond the detection range of the force gauge used. While this issue did not affect the relative comparisons among arrow types and targets, it does mean that the recorded force values reported here only capture the lower range of the arrow withdrawal
force values. Future studies should ensure to adopt force gauges with greater measuring capacities.

Taking these findings together, we suggest that edge serration on stone points, such as those associated with the Maros point, can provide functional benefits to the performance of stone-tip projectiles, though these effects are context-dependent. First, serrated points can produce deeper penetration than non-serrated points when the delivery velocity is above a certain threshold that gives the projectile point sufficient energy to tear through the target. The implication of this is that, if the serrated stone points were adopted for functional effects, a certain bow size and draw weight would have been required to achieve these effects in the past. Comparing the bow used in our experiment and that by Loendorf et al. (2015, 2017), this threshold of bow size is between 14 and 18 kg in terms of bow draw weight. As mentioned earlier, it is currently unclear whether increasing the bow draw weight beyond this threshold would widen the penetration difference between serrated and non-serrated points. However, if larger bows and higher projectile speeds were used, we expect to see a greater variation in the durability of the two arrow types. In our experiment, we observed that the serrated points tend to have more variable distributions of macrofracture on the tip than the non-serrated points due to the irregular edge morphologies. With higher projectile impact speeds, it is anticipated that these differences in macrofracture size and frequency would persist, if not widen (Iovita et al. 2014), which could affect the durability and reusability of the two arrow types. Other factors that influence the size of macrofracture scars and hence point durability include the angle of incidence, which would have also depended on the projectile impact velocity and the propulsion system (Coppe et al. 2022). Related to this, a higher percentage of the non-serrated arrows was broken than the serrated points after firing at the targets containing skin and/or bone. Although this difference in breakage proportion was not statistically significant in our sample, there is the possibility that variation in breakage rate may become more pronounced if the arrows were fired using larger bows. If this is the case, edge serration could represent a design strategy that improves both the penetration performance and durability of stone points, as opposed to other approaches to enhance projectile performance at the expense of durability, such as allowing arrows to break within target preys to increase tissue damage and bleeding (Rudner 1979).

Another implication of our findings is that the effect of serrated points varies by target type. The inclusion of skin and bone in our test targets reduced the penetration difference between the serrated and the non-serrated arrows. This variation in functional performance can help explain why we do not see a more widespread uptake of serrated points in the past. While edge serration on stone points is a global phenomenon, it is much less prevalent than other non-serrated point types perhaps because the functional advantage offered by edge serration is highly dependent on the context of use and the anatomy of the hunted prey (Vierra and Heilen 2020). Our experimental results suggest that serrated arrows would perform better than non-serrated arrows if the prey has thin skin (relative to the pig skin tested here) and/or more muscle mass. On the other hand, as noted earlier, there remains the possibility that the performance of serrated points would improve with the use of larger bows. Judging by the average penetration depth of the serrated points being consistently higher than that of the non-serrated arrows across all of our experiments, the penetration difference between the two arrow types may actually widen under the use of larger bows and become more systematic across different target types. Future studies can clarify this issue by testing a wider range of bow draw weights.

Importantly, the fact that serrated points can have a functional effect on projectile performance does not preclude the possibility that these edge modifications were embedded with stylistic and symbolic meanings in the past. Studies have suggested that serrated points are associated with warfare or the hunting of dangerous animals because of their perceived ability to create terrible wounds (Ellis 1997). It is entirely plausible that these social meanings were derived from empirical relationships. As mentioned already, experiments have demonstrated that serrated knives create markedly different damage than non-serrated knives on soft tissues (Pounder et al. 2011; Thompson and Inglis 2009). In our experiment, we also showed that serrated arrows required less force to withdraw from the ballistic gel target, implying that the serrated margins created larger wound tracks than the non-serrated margins in muscle-like tissues. These functional effects could have led edge serration to take up functional and social meanings, such that the morphological characteristics become associated with notions of lethality and violence. As a consequence, the production of edge serration on stone points may be applied to situations that were perceived to be dangerous or require more lethal weapons. Equally, we can envision these meanings to be attached to social groupings at a larger scale, where functional effects and social values become entangled in material expressions of identity and social relations (Loendorf et al. 2015; Loendorf et al. 2017). For instance, if edge serration was perceived as more dangerous and lethal, the trait could have been employed as a material symbol for intra- or inter-group aggression and competition. Of course, these scenarios are purely speculative at this stage. The point here is that, since edge serration is an ‘isochrestic’ part of the tool that delivers the functional outcome (i.e. cutting or penetration into the target) (sensu Sackett 1990), attempts to separate out the functional factors from the stylistic among the serration may be unproductive.
Maros points and the Toalean

As noted earlier, there is a general assumption in the archaeology literature that the Maros point of South Sulawesi represents the tip of projectile armature such as arrows. It is important to make clear that this assumption remains a hypothesis that needs to be tested against the archaeological record (Maloney et al. 2022; Perston et al. 2021a). However, if the Maros points were indeed used as arrowheads, the experimental findings here suggest the possibility that the serrated edge design was adopted for functional reasons in the mid-Holocene. While the actual increase in penetration depth by using points with serrated margins may not be vast when compared to non-serrated points, the difference could have contributed to the hunting success of certain prey types. In addition, the larger wounds produced by serrated points would cause more bleeding and are harder to heal. Considering these functional benefits, the appearance of the Maros points in South Sulawesi during the mid-Holocene may point to changes in foraging practices involving innovative strategies to increase hunting success. The unserrated, hollow-based Lompoa point (Perston et al. 2021b) that occurs in the Toalean thus may either represent unfinished Maros points, or be used for different prey types. To clarify these issues, detailed traceology studies are urgently needed to verify the function of these Toalean points (Maloney et al. 2022). To this end, our use-wear observations here provide an important point of reference for the identification of projectile use among serrated point types like the Maros point and the Mallindrug point. Namely, compared to non-serrated points where impact fractures tend to be limited to the distal apex, our experimental results show that serrated points can exhibit impact fracture not only at the apex but also along the adjacent lateral margins.

Aside from the Maros point and other retouched point types, several other Toalean artefact types have also been related to composite projectile weaponry, such as backed artefacts, sawlettes and bone points (Perston et al. 2021b). The co-occurrence of these novel tool forms indicates technological transformations in South Sulawesi during the mid-Holocene, possibly under backdrop of shifting environmental conditions. Based on the δ13C of epicuticular waxes from C4 plant and titanium concentrations in the sedimentary record of Lake Towuti, studies have shown a reduction in precipitation and an increase in open grassland in the region between ~9 ka and 3 ka (Russell et al. 2014; Vogel et al. 2015; Tamuntuan et al. 2015). A similar drop in δ13C during the early-mid Holocene indicating the onset of relatively dryer conditions was also observed in the environmental record of the nearby Lake Matano (Wicaksono et al. 2017). The sedimentary record at Lake Tondano in North Sulawesi also suggests increasing disturbance to surrounding forest vegetation in the mid-Holocene (Dam et al. 2001). Specifically, the diatom assemblage this time in the lake became dominated by littoral taxa, indicating a change to more shallow water and swampy conditions.

However, records from elsewhere in Sulawesi show somewhat different patterns for the early-mid Holocene. Data derived from Lake Lantoa in South Sulawesi indicates peak abundance of lowland forest types and arboreal taxa, as well as the expansion of tropical conifers between ~8 ka and 5 ka (Hamilton et al. 2019). Sedimentary cores from Mandar Bay in Central Sulawesi also do not show any decline in δ13C until 5000–4000 years ago (Wicaksono et al. 2017). These regional variations likely reflect heterogeneous Holocene climatic conditions across Sulawesi. Indeed, while much of the vegetation in Sulawesi today is characterised by evergreen rainforest due to year-round high precipitation, parts of Sulawesi, including South Sulawesi, are dominated by tropical deciduous forests because of the more pronounced dry seasons during parts of the year, caused by the southeastern trade winds bringing dry air from Australia (Wicaksono et al. 2017). There are signs that the trade winds from Australia strengthened in the mid-Holocene 8000–6000 years ago (Ding et al. 2013). The more intense dry seasons during this time would have led to shifts in the South Sulawesi vegetation, such as the increase of non-woody grasslands in place of closed canopy forest as documented in the Lake Towuti and Lake Matano sedimentary records mentioned above (Russell et al. 2016; Vogel et al. 2015; Wicaksono et al. 2017).

In this context, it is possible that the occurrence of the serrated Maros points and other Toalean tool types during the mid-Holocene signals a major reconfiguration in subsistence practices in response to changing resource availability. For instance, the fragmentation of closed-canopy rainforests and the expansion of grasslands could have led to greater seasonal variation in the distribution of animal and plant species (Simons and Bulbeck 2004), prompting past people to invest greater time and energy in the manufacture and use of technologies, such as projectile weapons, that can improve hunting success and buffer against foraging risk and cost (Bleed 1986; Torrence 2008; Hiscock 1994). Moreover, a decline in local resource abundance could have also promoted inter-group interactions over territorial boundaries and social arrangements for resource access and information sharing (Mackay et al. 2014; Ambrose and Lorenz 1990), with material culture playing a role in the maintenance of social cohesion under heightened social and economic tensions (Hodder 1979; David and Lourandos 1998; Clarkson et al. 2018; Hiscock 1994, 2018, 2021). From this perspective, the uptake and spread of the Maros point and other distinctive Toalean tools in South Sulawesi may be functionally driven but socially mediated, through the signalling and negotiation of social identity and relations within and between groups. This
process of social interaction can help explain the spatially circumscribed distribution of the Toalean techno-complex. As mentioned earlier, Bulbeck et al. (2000) noted that the distribution of ‘classic’ Toalean sites correlates with the current spread of the Makassar Austronesian languages in South Sulawesi, and proposed that Toalean assemblage variations towards the late Holocene were relate to the arrival of Austronesian speakers and the introduction of farming. Recent review by Perston et al. (2021a) demonstrates that this general geographic distribution for the Toalean still stands based on current archaeological evidence. However, given that the appearance of the Toalean predates the arrival of the Austronesian speakers, this geographic division between the Toalean/non-Toalean site distributions in South Sulawesi could reflect a deeper socio-cultural separation dated back to the mid-early Holocene, intertwined with regional environmental history.

Conclusions

The archaeological occurrence of serrated stone points is a global phenomenon, yet few experimental studies have investigated the possible effect of edge serration on the performance of stone-tip projectiles (Loendorf et al. 2015, 2017). Contrasting to previous findings by Loendorf et al. (2015, 2017), our results indicate that serrated points do produce deeper penetrations and possibly larger wound tracks under some settings, though these effects are complicated by the structural variation of the targets. The observations here suggest that the benefits offered by edge serration to projectile performance are not universal, but rather contingent on other contextual factors, including the projectile delivery system and the type of prey for which the points were used (Vierra and Heilen 2020). By clarifying the relationships among these different factors, it may be possible to better infer the range of technological behaviours associated with the application of serrated points in the past.

The experimental findings here suggest the possibility that the serrated margins on the Maros points of South Sulawesi were adopted to improve hunting success through the use of projectile armature. The occurrence of the Maros points and other Toalean tool types during the mid-Holocene in South Sulawesi signals major reorganisations in technological and foraging practices, possibly in relation to declining resource availability and heightened social interactions under drying conditions. In this setting, the functional and the symbolic aspects associated with the distinctive serrated margins may have become intertwined in ways that facilitated the maintenance and transmission of the Maros point overtime in the region.
| ID   | Type       | Shaft mass | Point mass | Total mass | Target            | Fracture group | Macrofracture location | Macrofracture termination |
|------|------------|------------|------------|------------|-------------------|----------------|------------------------|--------------------------|
| expn13 | Non        | 18.3       | 1.3        | 19.6       | Gel and bone      | Breakage       |                        |                          |
| exps2  | Serrated   | 18.6       | 1.6        | 20.2       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Step, hinge               |
| exps1  | Serrated   | 18.1       | 1.3        | 19.4       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Mix                       |
| expn11 | Non        | 18.7       | 2          | 20.7       | Gel and bone      | Breakage       |                        |                          |
| expn9  | Non        | 17.6       | 1.6        | 19.2       | Gel and bone      | Breakage       | Ventr                   | Tip                       | Feather, hinge            |
| expn4  | Non        | 18.6       | 2.2        | 20.8       | Gel and skin      | Breakage       |                        |                          |
| exps21 | Serrated   | 18.7       | 1.9        | 20.6       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Step, hinge               |
| exps11 | Serrated   | 19         | 1.1        | 20.1       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Mix                       |
| expn2  | Non        | 19.2       | 3.3        | 22.5       | Gel and bone      | Impact fracture | Both                    | Distal                   | Hinge and step            |
| exps30 | Serrated   | 17.4       | 3.1        | 20.5       | Gel and bone      | Impact fracture | Ventr                   | Distal, both lateral     | Step, feather             |
| expn16 | Non        | 18.2       | 2.4        | 20.6       | Gel and bone      | Impact fracture | Both                    | Distal                   | Feather, hinge            |
| exps19 | Serrated   | 18.6       | 1.9        | 20.5       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Step,hinge, feather       |
| exps17 | Non        | 18.7       | 2.9        | 21.6       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Step, hinge               |
| exps28 | Non        | 17.8       | 1.5        | 19.3       | Gel, bone, skin   | Breakage        | Both                    | Tip                      | Mix                       |
| exps29 | Serrated   | 15.6       | 1.6        | 17.2       | Gel, bone, skin   | Impact fracture | Both                    | Mix                      |                          |
| exps23 | Serrated   | 16.9       | 2.2        | 19.1       | Gel, bone, skin   | Impact fracture | Both                    | Distal, both lateral     | Step, feather             |
| exps5  | Serrated   | 17.3       | 1.9        | 19.2       | Gel, bone, skin   | Impact fracture | Both                    | Distal, both lateral     | Mix                       |
| exps35 | Serrated   | 16.9       | 2.2        | 19.1       | Gel, bone, skin   | Impact fracture | Both                    | Tip                      | Mix                       |
| exps27 | Non        | 23.1       | 1.2        | 24.3       | Gel, bone, skin   | Impact fracture | Both                    | Distal                   | Feather, hinge, step      |
| exps6  | Non        | 20.3       | 1.4        | 21.7       | Gel, bone, skin   | Impact fracture | Both                    | Distal                   | Hinge and step            |
| exps34 | Serrated   | 17.8       | 1.3        | 19.1       | Gel, bone, skin   | Impact fracture | Both                    | Distal, both lateral     | Mix                       |
| exps5  | Non        | 19.1       | 2.7        | 21.8       | Gel, bone, skin   | Impact fracture | Both                    | Distal, both lateral     | Step, hinge               |
| exps15 | Non        | 21.7       | 1.5        | 23.2       | Gel and bone      | Impact fracture | Both                    | Distal                   | Step, hinge               |
| exps8  | Non        | 20.1       | 2.3        | 22.4       | Gel and bone      | Impact fracture | Dorsal                  | Distal                   | Hinge and step            |
| exps24 | Serrated   | 18.3       | 1.5        | 19.8       | Gel and bone      | Impact fracture | Dorsal                  | Distal                   | Hinge and step            |
| exps13 | Serrated   | 18.3       | 1.9        | 19.2       | Gel and bone      | Impact fracture | Both                    | Distal                   | Hinge and step            |
| exps20 | Non        | 19.3       | 1.1        | 20.4       | Gel, bone, skin   | Breakage        |                        |                          |
| exps22 | Non        | 19.3       | 2.3        | 21.6       | Gel, bone, skin   | Impact fracture | Dorsal                  | Distal                   | Hinge and step            |
| exps15 | Serrated   | 17.9       | 2          | 19.9       | Gel and skin      | Impact fracture | Both                    |                          |                          |
| exps7  | Serrated   | 21.2       | 1.8        | 23         | Gel and skin      | Breakage        | Both                    | Distal                   | Hinge and step            |
| exps2  | Non        | 19.2       | 3.3        | 22.5       | Gel and bone      | Impact fracture | Dorsal                  | Distal                   | Step                      |
| exps10 | Serrated   | 17.6       | 1.9        | 19.5       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Step, hinge, feather      |
| exps34 | Non        | 18.2       | 1.1        | 19.3       | Gel, bone, skin   | Impact fracture | Dorsal                  | Distal                   | Feather                   |
| exps9  | Serrated   | 19.2       | 3.1        | 22.3       | Gel and bone      | Impact fracture | Both                    | Distal, both lateral     | Hinge and step            |
| exps20 | Serrated   | 19.8       | 3          | 22.8       | Gel and bone      | Impact fracture | Ventr                   | Distal                   | Step                      |
| exps4  | Serrated   | 17.7       | 1.3        | 19         | Gel and bone      | Impact fracture | Ventr                   | Distal                   | Hinge and step            |
| exps3  | Serrated   | 18.9       | 2.4        | 21.3       | Gel, bone, skin   | Impact fracture | Both                    | Distal, both lateral     | Hinge and step            |
| exps38 | Serrated   | 16.9       | 1.1        | 18         | Gel, bone, skin   | Impact fracture | Both                    | Distal                   | Feather, hinge            |
| exps8  | Serrated   | 18.7       | 1.9        | 20.6       | Gel, bone, skin   | Impact fracture | Ventr                   | Distal                   | Feather                   |
| exps37 | Non        | 18.6       | 2          | 20.6       | Gel, bone, skin   | Breakage        |                        |                          |
| expn10 | Non        | 17.6       | 1.9        | 19.5       | Gel and bone      | Breakage        |                        |                          |
| expn12 | Non        | 17.3       | 2.3        | 19.6       | Gel and bone      | Breakage        |                        |                          |
| expn20 | Non        | 18         | 1.4        | 19.4       | Gel and bone      | Breakage        |                        |                          |
| expn27 | Non        | 23.1       | 1.2        | 24.3       | Gel, bone, skin   | Breakage        |                        |                          |
Table 3 (continued)

| ID   | Type   | Shaft mass | Point mass | Total mass | Target                | Fracture group | Macrofacture location | Macrofracture termination |
|------|--------|------------|------------|------------|-----------------------|----------------|------------------------|-----------------------------|
| expn30 | Non   | 16.9       | 1.8        | 18.7       | Gel, bone, skin       | Breakage       | Surface               |                            |
| expn36 | Non   | 19.9       | 1.2        | 21.8       | Gel, bone             | Breakage       | Edge                  |                            |
| expn9  | Non   | 17.6       | 1.6        | 19.2       | Gel and bone          | Breakage       | Edge                  |                            |
| exps12 | Serrated | 18.6      | 1.6        | 20.2       | Gel and bone          | Breakage       | Surface               |                            |
| exps36 | Serrated | 17.4      | 1.2        | 18.6       | Gel, bone, skin       | Breakage       | Edge                  |                            |
| exps6  | Serrated | 18.2      | 2.2        | 20.4       | Gel and bone          | Breakage       | Surface               |                            |

Appendix

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