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The harpoon stands yonder: Shape variation and functional constraints in Mesolithic complex weapon points from the circum-Baltic Sea area

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ABSTRACT

Mesolithic harpoons are structurally complex weapon points and significant sources of archaeological information. Nonetheless, separating different types of information inherent in harpoon point shapes (e.g., aspects relating to mechanical performance, personal or group craft variation and chronology) using descriptive approaches is difficult. In this study, we employed an exploratory geometric morphometric approach to the analysis of 28 Mesolithic harpoon points, and 144 undated harpoon points from the circum-Baltic Sea area in order to retrieve both functional and spatiotemporal information. By analyzing harpoon structure statistically through (i.) a shape proxy (harpoon silhouette) and (ii.) harpoon sub-structures (barbs), we have been able to reveal information related to both variation in shape convention and functional constraints. Barb shape results revealed statistically significant chronological and geographical groupings with spatiotemporal barb-shape trajectories made visible and objective evaluation of how barb-shape conventions impacted functional variation. In addition, harpoon silhouette shape distributions were shown to have potential as sources for robust artifact classifications in relation to functional constraints and raw-material engagement. These results suggest that morphometric approaches similar to the ones we have employed offer promising ways of addressing specific archaeological questions in the context of harpoon point shapes and, more generally, other complex weapon point forms.

1. Introduction

Morphological studies in archaeology are commonly based on analyses of artifacts with comparable structures. While a standard typological analysis is an appropriate approach for identifying stylistic groups, typological schemes have not yielded descriptions sufficient for grouping structurally complex weapon points in relation to a variety of other variables such as their mechanical and/or spatiotemporal dimensions. The logic behind this limitation reflects the observation that the more complex an artifact is structurally the more likely corresponding structures cannot be found on all specimens included in a group of complex artifacts. However, understanding the role(s) of complex artifacts is important as they present a rich blend of influences that cannot be captured by the analysis of morphologically simpler objects (for structural complexity as a scalar of information c.f., Thom, 1975: 144f). In theory, the morphological study of complex weapon points should facilitate a wide range of investigations pertaining to societal, environmental, physical and physiological practices.

A classic example of a structurally complex hunter-gatherer weapon point is the Early Holocene osseous barbed point with a structure for rope attachment, often referred to as a "harpoon" (for a discussion of the archaeological definition, see Supplementary Materials Appendix 1). We consider harpoons, or harpoon points, to be complex weapon points since they reflect the properties of an artifact with at least three different components (point, rope and shaft), whose positions can change relative to each other during use (Kelly, 2013; Oswalt, 1976: 120). The hierarchical relationship between a structure (harpoon point) and its substructures (barbs, rope attachment/base) reflects that complexity (c.f., Simon, 1991). In the Mesolithic circum-Baltic Sea area, barbed points from presumed harpoons represent an artifact category potentially used in diverse environments, contexts and against a wide range of prey (e.g., Weniger, 1995, 2000; Pétillon, 2009; Ickerodt, 2013; Christensen et al., 2016; Pettitt et al., 2017). Major environmental and climatic events occurred around the Baltic Sea during the Mesolithic, such as sea-level transgressions, the 8.2 k BP cold event and the Storegga tsunami (e.g., Bondevik et al., 2003; Alley and Ágústsdóttir, 2005; Stattegger and

Abbreviations: GM, geometric morphometrics; PCA, principal component analysis; CVA, canonical variate analysis.

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Leszczyńska, 2023). These events resulted in a wide range of societal responses that might potentially have left their imprint on harpoon point morphology.

Mesolithic harpoon points from the Baltic Sea region are popular components in archaeological exhibitions and subjects of typological study. Several typologies have been used to describe and classify Mesolithic harpoons and other barbed points into morphological subgroups (Clark, 1936; Andersen, 1971, 1975; Kozłowski and Kozłowski, 1975, 1977; Verhart, 1990; Andersen, 1996; Vankina, 1999; Andersen and Vang Petersen, 2009; Galiński, 2013; Gummesson and Molin, 2020). These subgroups have also been found to have geographical and chronological boundaries (Verhart, 1990; Andersen, 1996; Andersen and Vang Petersen, 2009). The relation between specific harpoon point subgroups, their properties and their functional roles have been discussed by Clark (1936), Larsson (1999) and Vang Petersen (2009). However, no typological approach employed previously was based on a systematic analysis of the different variables (geography, chronology, function) that might have played a key role in constraining the shapes of the individual harpoon components, and none of these previous results were evaluated statistically. Our primary goal was to offer this type of explicit morphological data analysis in combination with statistical testing.

Geometric morphometric (GM) methods have been applied in a wide range of archaeological studies since the beginning of the 21st century (Lycett et al., 2006). With regard to projectile points, primarily lithics have been analyzed with the aim of retrieving either functional information or to identify geographical/chronological groups (e.g., Charlin and González-José, 2012; de Azevedo et al., 2014; Chacón et al., 2016; Fox, 2015; Serwatka and Riede, 2016; MacLeod, 2018; Serwatka, 2018; Buchanan et al., 2020; Matzig et al., 2021). In some cases, canonical variate analysis (CVA) was used to study patterns of between-groups lithic point morphological variation (Thulman, 2012; Smeyatsky, 2014; Eren et al., 2015; MacLeod, 2018; Smith et al., 2021; Smith and Reid, 2022).

From a morphometric perspective, technological complexity and the presence of many structural elements, such as multiple barbs, often renders artifact structures non-comparable due to variations in the kind, number, presence, quality and/or preservation of the subunits. In a recent GM analysis of Paleolithic and Early Mesolithic barbed points (Tsirintoulaki et al., 2023), sub-structures were regarded as "techno-functional components" (c.f., Doyon, 2019) to analyze artifacts such as those we consider as being complex in this study. This analysis revealed low levels of sub-structure shape normativity in relation to the archaeological periods examined.

Recent developments in methods of archaeological group classification (Sholts et al., 2017; MacLeod, 2018; Salili-James et al., 2022;) show that investigations of normativity, (i.e., shape conventions and the identification of specific shape variables) are possible under a variety of analytic approaches. In this study, we employed a specific exploratory, GM-based approach to the quantitative assessment of complex weapon points in terms of overall artifact structures and one of its sub-structures to identify both functional and non-functional information. The proximate aims of our investigation, were as follows:

1. To assess whether different types of harpoon structures, grouped in relation to archaeologically relevant information (geographical regions and chronological periods), display different morphologies.

2. To determine how any groupings of different structures discovered through the application of geometric analyses relate to one another.

3. To test the use of ordination-space models to improve the interpretation of distributions of complex archeological artifacts in multivariate ordination spaces.

2. Materials and methods

2.1. Research approach

In contrast to earlier studies based either on harpoon shapes or types (Clark, 1936; Andersen, 1971, 1975; Kozłowski and Kozłowski, 1975, 1977; Verhart, 1990; Andersen, 1996; Galiński, 2013), single attributes/elements (Andersen and Vang Petersen, 2009; Gummesson and Molin, 2020) or combinations of single attributes/elements (Tsirintoulaki et al., 2023), our approach involved consideration of both entire harpoon point shapes and single shape components, both together and separately, by sampling comparable outline configurations. These structures are (i.) barbs and (ii.) full-body silhouettes (Fig. 2). Barbs are protruding sub-structures that obstruct projectile extraction and appear in series on each harpoon. Full body silhouettes are representations created by reconstructing the original shape of the projectile preform before the barbs were carved. In this way we considered a structure specific to both craft processes and raw material properties. The silhouette was also regarded as a proxy for the plan shape of the wound the harpoon point would create when delivered (the wound cavity); thus, it reflects some functional properties related to the structure of the entire delivery system (e.g., shaft, spearthrower, bow), the targeted animal and the hunting environment. In the case of harpoon points, via minimization of (potential) interference between constraint domains, we propose that the analysis will provide comprehensive information if the specimens are considered as consisting of two structures - barbs and silhouettes. By including the different hierarchical levels of the harpoons, through the selection of the proxy structure that, from a functional perspective, is at the highest organizational level offered by the material, the silhouette, i.e. the plan shape of the wound cavity, and the only sub-structure that exists as a group, the barbs, we also explored the complexity of the object.

Our approach included a specific way of exploring multivariate ordination spaces. To gain additional information, separate procedures were used to identify two different traits, shape commonalities, i.e. convention, and functional constraints (c.f. White, 2013). Shape convention may embody characteristics common to specimens fabricated by one archaeological group. If so, this indicates a spatiotemporal relation between the artifact makers. Functional constraints are characteristics that limit what actions the specimen might support. Since most specimens cannot be classified according to a conventional archaeological group scheme, chronology and geography were employed as grouping variables. Here, canonical variates analysis (CVA, see Campbell and Atchley, 1981) was used to test shape data for the existence of such groups. Similar approaches to group-based morphological analyses have been employed in evolutionary biology, environmental analysis and functional morphology (e.g., Anderson and Willis, 2003; Figueirido et al., 2011; Sievwright and Macleod, 2012; Cooke and Terhune, 2015; Marrama and Kriwet, 2017; MacLeod and Kolska Horwitz, 2020). However, available environmental and functional information is insufficiently detailed to be used to perform functional group tests on our harpoon sample. Accordingly, a prior principal component analysis (PCA, see MacLeod, 2007) was used to explore our shape data for variance trends that might reveal functional groups. We argue here that clusters of artifacts within patterns of distribution aligned with the directions of maximum pooled-sample shape variation, if present, might provide an indication that functional constraints were involved in artifact design, especially when compared to group-optimized CVA results.

We also adopted a multiple-barb approach. Barbs from a single harpoon were treated as individual specimens because numerous influences effect their shapes. Obviously, the form of the raw material, in relation to the position of the barb, can dictate its final shape. For example, in a previous study it was proposed that creating two harpoon points from one metapodial was responsible for a large component of intra-specimen variation (David et al., 2022). Generally, in traditional crafts, the creation of an artifact involves engaging with constraints

imposed by raw materials and available tools rather than imposing an abstract blueprint (c.f., Ingold, 2000: 345f). As a consequence, artifact substructures made by one person should be considered individual, albeit related, specimens. Additionally, barb shapes are influenced by usage. Hence, individual barbs can be re-shaped secondarily by use-wear, fractures and, eventually, by manual resharpening.

Possible biases resulting from our multiple-substructure approach were considered explicitly in our analysis by tracking of barb shapes from each harpoon in the PCA and CVA ordination spaces to avoid over-interpretation of our results. Thus, our GM-based exploratory approach created an information-rich context within which both multiple-barbs and harpoon point silhouettes can be analyzed and compared both separately and in combination with similarity/difference patterns assessed, in order to maximize the type and diversity of archaeologically relevant information gained and facilitate robust statistical testing.

2.2. Material

Our sample included, to the best of our knowledge, all direct radiocarbon-dated harpoon points or harpoon points associated with radiocarbon dates, (72 barbs and 18 silhouettes, Fig. 1). Dated specimens were assigned to chronological (Early, Middle, Late) and geographical (West, Central, East) groups (see Supplementary Material Appendix 1). In addition, we selected a sample of undated specimens based on the geographical division used for the dated specimens. This undated sample included 392 barbs and 129 silhouettes. The western part of the circum-Baltic Sea area was represented by mostly known and published specimens from west of Oder and Öresund, the central part of the region was represented by all known published harpoons from Sweden and the Eastern part by the material from Lake Lubāns, Latvia. All harpoon specimens included in our sample are listed in Supplementary Materials Table 1, and sampling and classification criteria are listed in Appendix 1.

In order to analyze as large and widely-spread sample as possible, published 2D images were used as specimens.

2.3. Method

2.3.1. Digitization

All barbs were cropped from the harpoon point images and silhouettes were created by shading areas between barbs and attachment protrusions (Fig. 2a, 2b, 2d). Silhouette forms were quantified via the collection of evenly spaced semilandmark points between two registration landmarks, the harpoon point's tip and base (Fig. 2c). Barb shapes were represented by a sequence of semilandmarks used to represent the forms of open blade outlines along with three registration landmarks (Fig. 2e). The purpose of this procedure was to ensure precise geometric matching of semilandmark points across the entire outline (see MacLeod, 1999). The first landmark (also the starting point of outline digitization) was placed at the intersection of the barb and its proximal junction with the harpoon point, the second at the barb tip and the last at the junction between the barb blade's ventral outline and the distal junction of the harpoon point (Fig. 2e). These landmarks were used to subdivide the open curve of the barb outline into two segments with the outline form being represented by a series of evenly spaced semilandmarks located along each barb outline segment (see MacLeod, 1999). This digitization procedure resulted in two datasets: one documenting 2D barb outlines and the other documenting 2D silhouette outlines.

2.3.2. Geometric morphometric analysis

Our GM analysis was performed using a modified version of the extended eigenshape procedure (MacLeod, 1999), involving separation of the barb and silhouettes into outline segments at the landmarks, separate determination of the number of semilandmark points necessary to represent the shapes of each outline segment to a specified degree of accuracy across all specimens in the sample, alignment of the landmark-semilandmark outlines (including size standardization) using the Procrustes GLS procedure (Rohlf and Slice, 1990), and reduction of the dimensionality of the shape-representation systems via PCA. Various stopping rules can be used to determine how many principle components should be discarded to avoid over- or underestimation (Peres-Neto et al., 2005). In this study, dimensionality was reduced by retaining only the number of sequential principal components that, together, represent

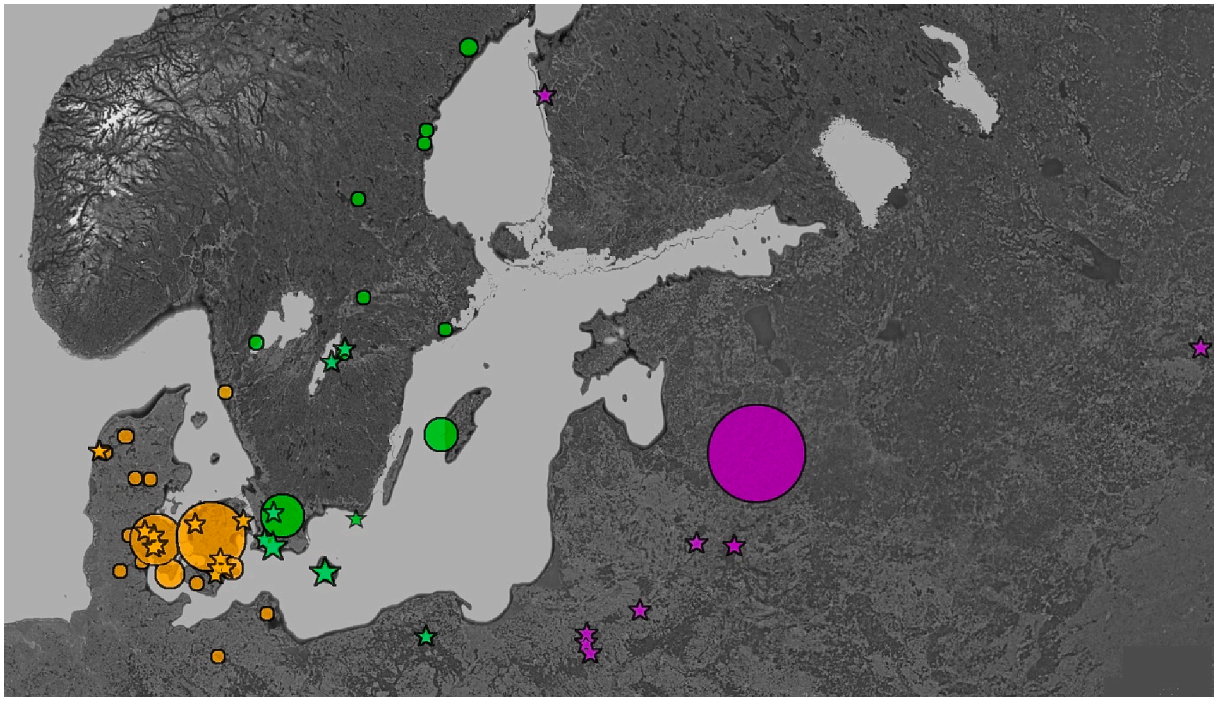


Fig. 1. Map of sites with harpoon points from the circum-Baltic Sea region used in this study. Stars: dated specimen or sites; Circle: undated specimens. The color code shows the geographical scheme used to test geographical shape group differences (yellow-West, green-Central, purple-East).

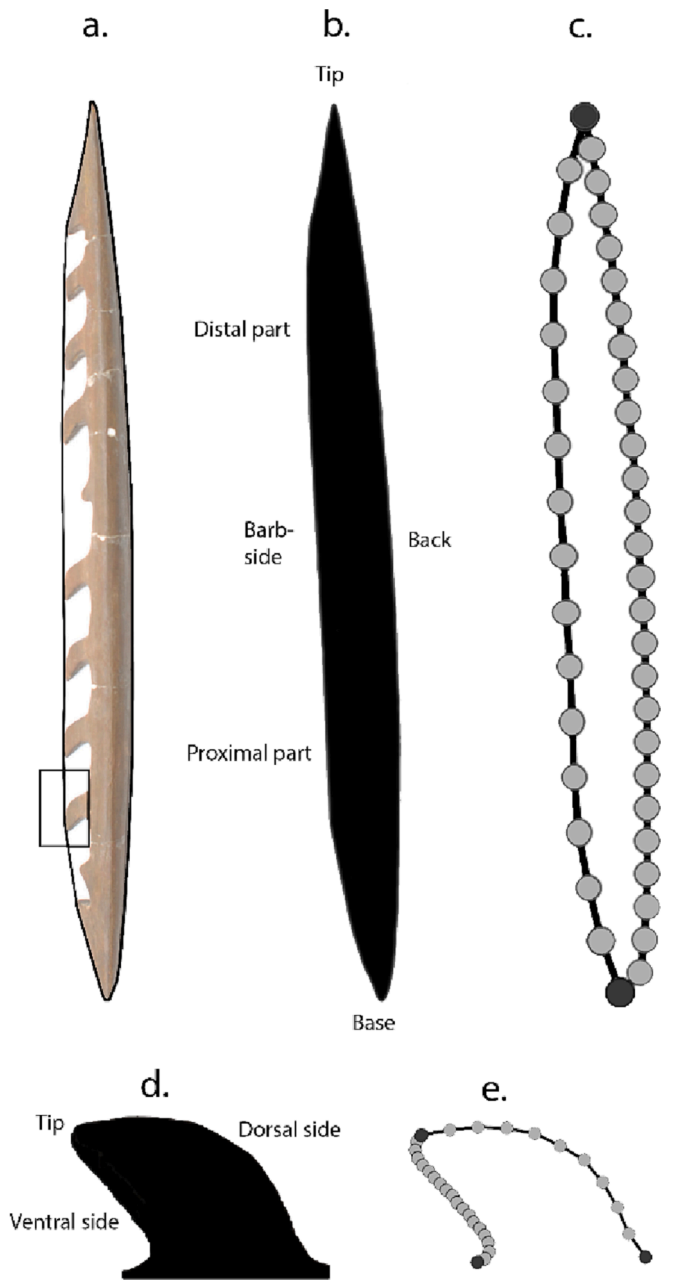


Fig. 2. a: Silhouette (outline) and barb (box) sampling procedure of the Opplimen harpoon point. b: Silhouette terminology c: Silhouette landmark placement (black) and example of semi-landmark placement (grey) d: Barb terminology e. Barb landmarks (black) and example of semi-landmarks (grey). Photographed at the Swedish History Museum and published with permission.

Table 1
Dimensionality reduction results for circum-Baltic Sea area harpoon datasets.

Dataset	PC1 Variance	No of Eigenvectors Retained	Total Shape Variance of Retrained Eigenvectors
Chronological multiple-barb	56.88	5	95.93
Geographical multiple-barb	72.64	5	96.79
Undated multiple-barb	48.06	6	95.83
Dated silhouette	54.01	8	95.92

95 percent of the observed shape variation across the pooled-specimen dataset. Our PCA results were also used in the analysis of pooled-sample barb-shape variation, primarily to examine our outline data for the presence of functional constraints.

2.3.3. Statistical analysis

Subsequent to dimensionality reduction via PCA, a CVA was performed to find a combination of scores along each of the retained PC axes that maximally separated group centroids relative to group variances. The resulting artifact shape ordinations provided information used to test group-centroid separations statistically. A CVA of a reduced set of PCA coordinate positions tests the hypothesis that artifact groups designated a priori either do, or do not, have similar average shapes. If the predefined groups do not cluster into different shape regions it means linear procedures cannot find a shape-related distinction between these groups. If the predefined groups do cluster it means such distinctions do exist. The significance of these distinctions was tested using two statistical procedures, the Log Likelihood Ratio and a Hotelling's T^2 (Manly et al., 2017). The geometric character of these shape distinctions was visualized in terms of the original outline data using the PCA/CVA axis-modelling procedures (MacLeod, 2009).

For the multiple-barb analysis, dated specimens were assigned to chronological and geographical classification schemes as described above (see also Supplementary Material Appendix 1, Fig. 1) with undated specimens being assigned according to the geographical classification scheme. However, dated chronological and geographical datasets were non-identical to reduce the influence of spatial variables in the chronological dataset and temporal variables in the geographical dataset. As a consequence, only Early Mesolithic specimens were included in the geographical analysis and Early Mesolithic Eastern specimens were subtracted from the chronological analysis. For the silhouette analysis, because of the small sample size of dated specimens, groups were defined by combining chronological and geographical distribution: Early Mesolithic, Middle Mesolithic, Late Mesolithic West/Central and Late Mesolithic East.

3. Results

3.1. PCA for data reduction

Results of our PCA-based dimensionality-reduction analyses are presented in Table 1. Note the similarity in the number of retained eigenvectors for the chronological and geographical multiple-barb datasets indicating that overall retained pooled-sample shape-variance proportions are similar. The chronological dataset exhibited a markedly less efficient summarization relative to the geographical dataset. This result suggests that greater barb shape variance typifies the former collection. The even less efficient summarization for the undated multiple-bard dataset was expected due to its larger size. Still, the 95 percent retention threshold was able to be reached with the addition of only a single extra eigenvector. The dated silhouette exhibited the least efficient summarization of the datasets analyzed due, no doubt, to its greater size which provides greater opportunity for the inclusion of substantially divergent shapes.

3.2. Chronologically delimited barb groups

3.2.1. PCA ordinations

For the chronological multiple-barb datasets, information can be gained by comparing shape-ordination patterns in the space formed by the first two PC eigenvector axes to expectations derived from functional considerations. Notably, Fig. 3a shows the first axis revealed no groupings or obviously interpretive patterns, while chronologically delineated harpoon barb-shape groups exhibited distinct shape-variation trends along PC2. There, Early Mesolithic barb specimens projected to positions higher on the PC2 axis than those from the Middle

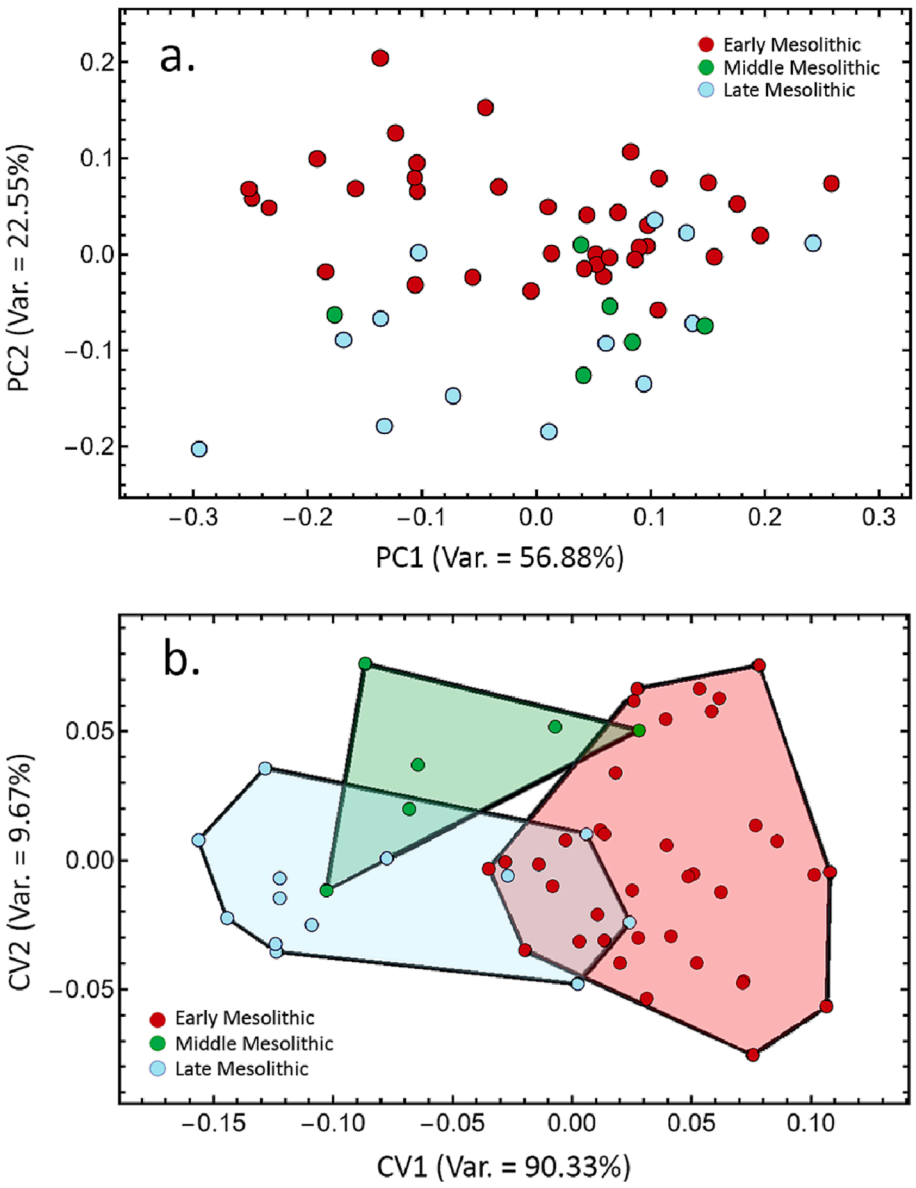


Fig. 3. PCA and CVA ordinations of barbs assigned to chronological groups. Note how these ordinations reveal different distribution patterns: a. chronological groups are unaligned to PC1, but well aligned to PC2. b. Despite (apparent) broad between-groups overlap in the PCA shape space the CVA result confirms that significant distinctions between dated barb shapes exist.

Mesolithic and Late Mesolithic.

Shape models calculated from the eigenvector equations of these axes reveal their geometric character (Fig. 4a, 4b). Along the PC1 axis low projection scores were given to barbs exhibiting a recurved dorsal segment and a highly recorded ventral segment (Fig. 4a). High scores were given to barbs with convex dorsal segments and concave ventral segments. From an archaeological perspective, PC1 shape variation appears to reflect the relative size of the barb tip. Consequently, PC1 scores might reflect predicted effects of use-wear and re-shaping. In fact, the photograph of the Abelskov barbs could be used to guide an interpretation of PC1 as a vector capturing the use-wear aspect of shape variation. Barbs from the Abelskov harpoon point had PC1 scores between −0.2 and 0.2 with the digitized photograph (Andersen and Vang Petersen, 2009: 37) clearly indicating that two barbs are intact, while the rest were either fractured, reshaped or worn down.

Shape variation along PC2, in contrast, appears to reveal shape differences related to original barb-designs, i.e. the chronological groups. Barbs assigned low scores on this axis were characterized by long, flat dorsal segments with distinct tips and long ventral surfaces with recurved termini. Barbs assigned high PC2-axis scores exhibited distinctly convex dorsal segments, blunt tips and rounded ventral surfaces (Fig. 4b). Since PC2 represents c. 23 percent of the pooled shape variation, these results indicate that between-groups differences not only reflect separate shape conventions, but were sufficient to effect the functional qualities of these sub-structures. However, it should also be noted that shape variation within Early and Late Mesolithic barb groups showed that potential internal functional-design disparity was of the same magnitude, at least so far as such variation is represented on this eigenvector axis.

3.2.2. *CVA ordinations*

For the chronologically grouped barb shapes, a CVA of PCA scores separated chrono-group means successfully, even though group domains were not mutually exclusive (Fig. 3b). Here, CV1 accounted for 90.33 percent of the between group-means shape variation and projected the majority of Middle and Late Mesolithic specimens to low positions along the discriminant vector/axis. The majority of Early Mesolithic specimens projected to high positions along CV1 with the zone of overlap

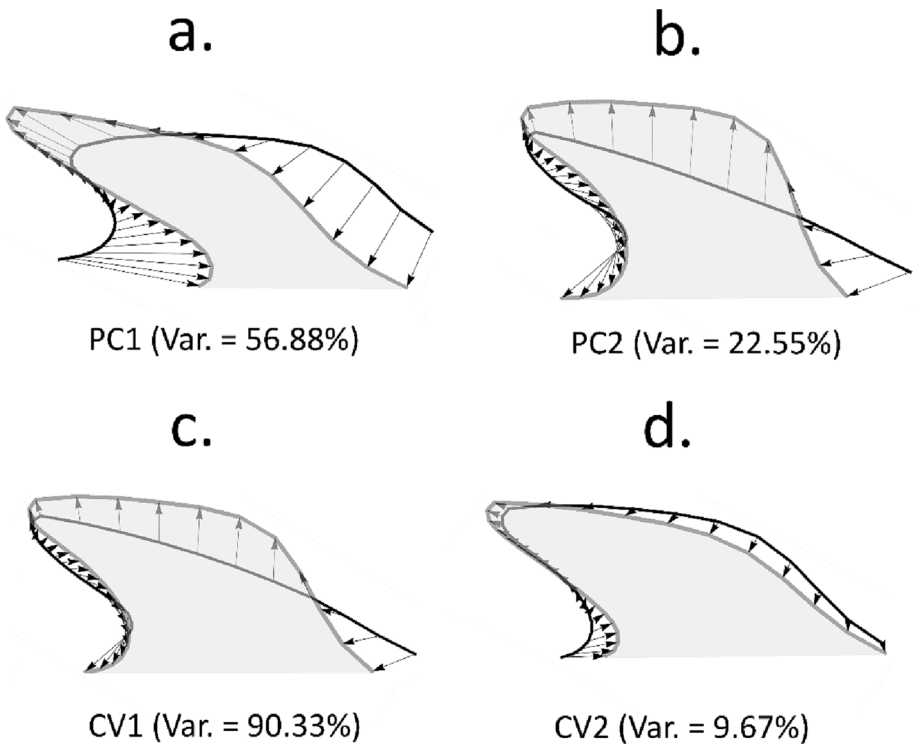


Fig. 4. Idealized geometric models of shape contrasts along the PC axes 1 and 2 (a,b) and CV axes 1 and 2 (c,d) for the chronologically assigned barb groups. White corresponds to the hypothetical specimen shape with the lowest projected score along eigenvector axes and light grey to the specimen with the highest projected score. Arrows show corresponding landmark displacement.

between all groups ranging to ± 0.04. Two Middle Mesolithic specimens and four Late Mesolithic appeared to be outliers relative to their assigned group. Along-axis CV1 models exhibited a pattern of shape variation similar to that of the pooled-sample PC2 models for the same dataset (Fig. 3c).

The CV2 eigenvector accounted for the remaining 9.67 percent of variation in group mean shapes and dominantly separated high Middle Mesolithic from low Late Mesolithic barb shapes (Fig. 3b). For this axis shape differences were minute. Lower scores were associated with slightly more convex dorsal segments and rounded ventral surfaces relative to higher scores (Fig. 4d).

Statistical analyses of these results showed that there was a significant ($\alpha \leq 0.05$) separation between the group-centroids of this admittedly small sample (Table 2). However, the shape outliers present in our sample indicated that a large, and overlapping, range of barb outline shapes were being used by each age cohort. In contrast to the PCA results, our CVA results managed not only to separate Early Mesolithic barbs from Middle and Late Mesolithic, but also revealed differences between Middle and Late Mesolithic group mean outline shapes. Additionally, in the CVA plot, several outliers were distributed closer to the group means of chrono-groups that differed from the one to which they had been assigned on the basis of available chronological evidence.

Table 2
Harpoon group separation results.

Dataset	Log likelihood ratio	Bootstrap Log likelihood ratio	Hotelling's T^2	Bootstrap Hotelling's T^2
Chronological multiple-barb	5.937×10^{-6}	0.000	5.313×10^{-6}	0.000
Geographical multiple-barb	7.651×10^{-8}	0.000	0.054	0.000
Undated multiple-barb	0.000	0.000	6.661×10^{-14}	0.000
Silhouette	18.214	22.100	86.754	81.300

Together, these CVA results indicated the presence of broad chronological differences in barb-shape design. However, it was also evident that chronological factors alone cannot be used to categorize specimens based on outline shape (see Discussion).

3.3. Geographically delimited barb groups

3.3.1. PCA ordinations

For the geographical dataset, the PC1 axis ordination indicated that shape variance was largely controlled by regional contrasts. As a group, eastern-Baltic barbs tended to have shapes that differed from those of western and central regions (Fig. 5a). Shape changes along this axis represented a shift from barbs with distinctively convex dorsal segments, pointed tips and rounded ventral segments to barbs with marginally convex dorsal segments, blunt tips and short ventral segments perpendicular to the dorsal surface (Fig. 6a). However, all eastern-barb PC1 eigenvector scores higher than 0.2 were represented by barbs from a single specimen (circled in Fig. 5a). Since the distribution of barbs from one harpoon point can be separated in such a manner, our results suggest this harpoon differed from all others. This finding may indicate, for example, the presence of a weapon point with a distinct functional role.

For this dataset PC2 shape contrasts were less informative (Fig. 6b). Barbs that projected to high PC2 positions had more convex dorsal segments and with more rounded ventral segments. Even though use-wear could not be rejected as the source of these shape disparities, the slight alignment of the pre-defined Eastern group with the PC2 axis suggested these shape contrasts might be related to differences in craft convention. In this context, it was notable that barbs assigned to the central group formed two subgroups.

3.3.2. CVA ordinations

For our geographically delimited barb outline-shape dataset CV1 accounted for 91.36 percent between-groups mean-shape variation with

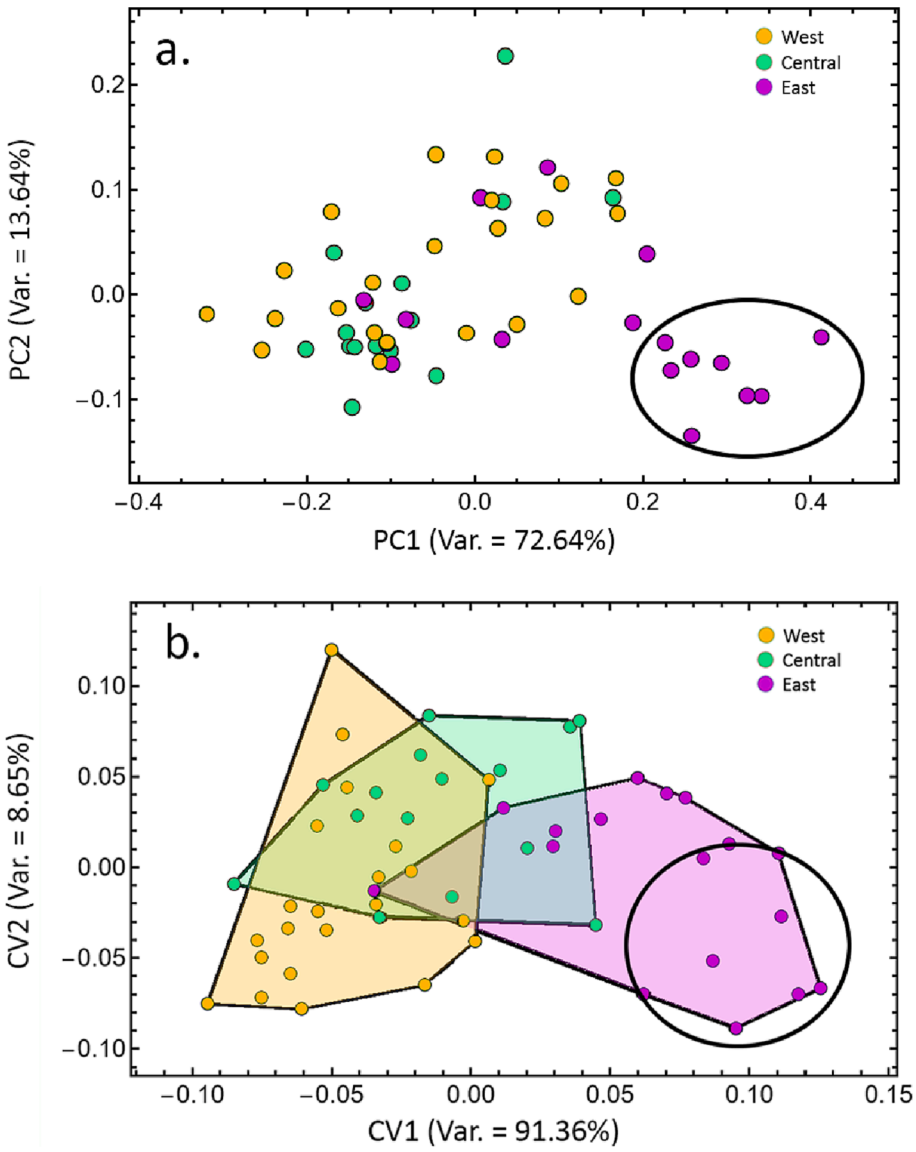


Fig. 5. A PCA and CVA ordination results of geographically grouped barb shapes. a. Barb-shape ordinations for pooled groups PCA eigenvectors 1 and 2. b. Barb-shape ordinations for CVA eigenvectors 1 and 2. Circled specimens belong to the harpoon point referred to as an outlier in the text.

western barbs projecting to low positions and Eastern barbs to high positions with central Baltic barb shapes being distributed in between. These results (Fig. 5b) demonstrated that separation of geographically defined group means could be accomplished though, in this case, overlap between the western and central groups was substantial. However, eastern and western group domains were mutually exclusive, except for a single shape outlier.

Along-axis shape CVA models (Fig. 6c) showed low scores along the geographic CV1 axis to be associated with distinctly convex dorsal barb outline segments, pointed tips and long, flat ventral segments with rounded termini. High scores on this axis represented barbs with convex dorsal segments, blunt tips and short ventral segments with recurved termini, almost perpendicular to the dorsal segment. Even though barbs from the outlier harpoon point were responsible for the distinct along-axis shape contrasts (circled specimens Fig. 5b, 6c), there were significant differences between western and eastern barb shapes. The dorsal segments of western barbs were more ascending and convex, clearly indicating different craft conventions. Additionally, central barb specimens were distributed within both western and eastern group domains, which lent support to the presence of spatiotemporal trajectories (see Discussion).

The geographic CV2 axis accounted for 8.65 percent of between-groups mean-shape variation and separated the central group mean (high projected scores) from the group means associated with western and Eastern Baltic barb outline shapes (Fig. 5b). Here, barb outline shapes assigned low CV2 scores exhibited slightly convex dorsal segments, blunt tips and rounded ventral surfaces, while those with high scores exhibited ascending, distinctively convex dorsal surfaces, pointed tips and long, flat ventral segments with recurved termini (Fig. 6d). If outlier barbs are excluded from the interpretation of the CV plot, CV2 had no effect on group mean separation. Instead, this plot revealed group outline-shape disparity. Since shape contrasts were related to tip protrusion and dorsal curvature, this disparity may be related to how sensitive the structure is to craft variability and physical influences (e.g., use-wear). In our dataset, western barb shapes had the highest variability and the most pronounced tips with intricate curvature, while eastern barbs the lowest variability, the least pronounced tips and least elaborate curvature.

To validate the ability of our analysis to identify geographical barb-shape variables, a CVA was also performed on an augmented dataset of 392 undated barbs (including specimens that are potentially Paleo- or Neolithic) from Sweden and Lake Lubāns. Results of this analysis

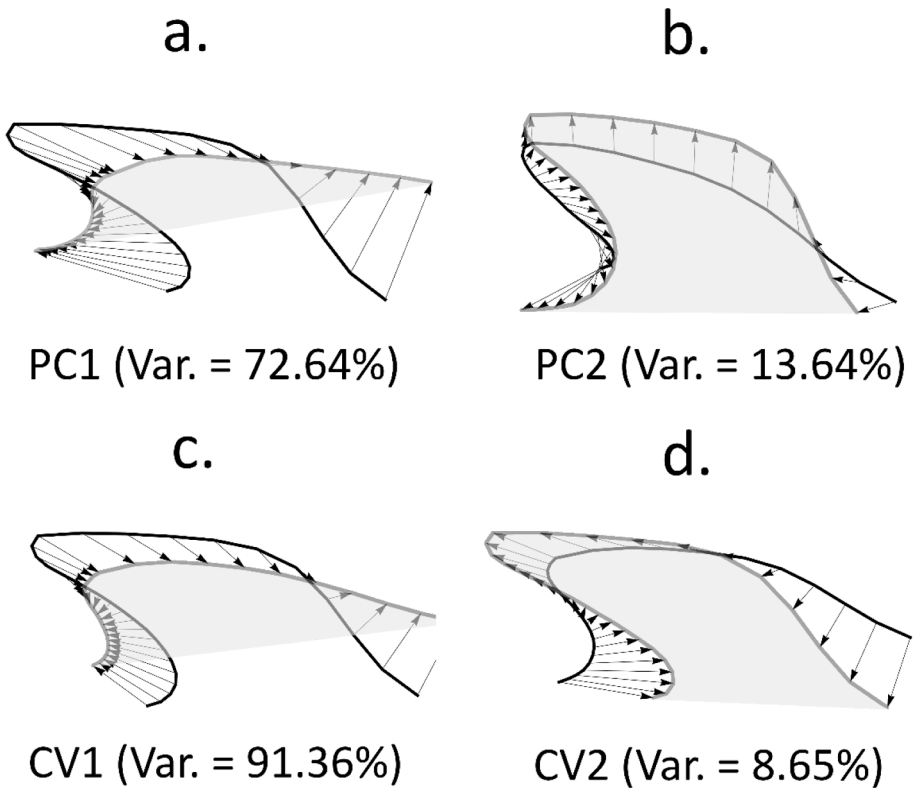


Fig. 6. Models represent shape contrasts along the PC (a, b) and CV (c, d) axes for the geographically assigned barbs. Shading and arrow conventions as in Fig. 4.

showed that these geographic group means could be separated with statistical significance (Table 2). For this expanded dataset, CV1 accounted for 72.52 percent of between-groups mean-shape variation and separated central and eastern group means, from the western group mean. Similarly, CV2 accounted for 27.48 percent of between-groups mean-shape variation and separated group means for the central and eastern groups (Fig. 7). Our results documented a marked separation between barb shapes from sites around the Baltic Sea Basin (Central, East) and sites situated close to the North Sea (West). To a lesser extent, specimens from the western side of the Baltic Sea basin (Central) could be separated from the eastern Baltic specimens (East). Hence, from a long-term perspective, physical geography seems to be consistent (or associated) with an influence on circum-Baltic Sea barb shape variation regardless of other factors.

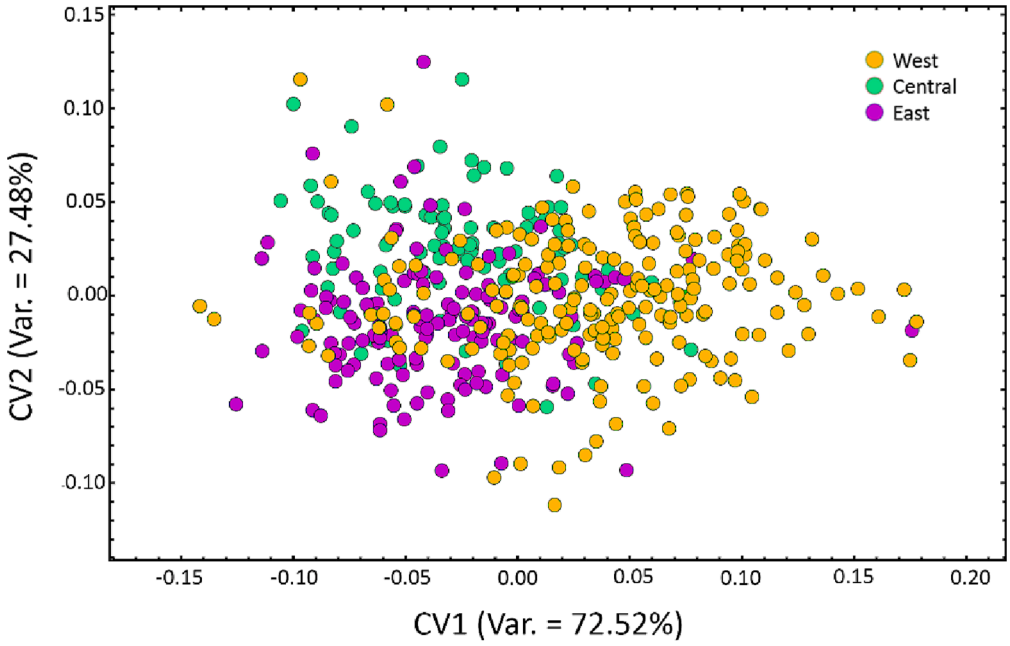


Fig. 7. CVA of undated barbs from West, Central and East circum-Baltic Sea regions have different shape means.

3.4. Harpoon silhouettes

3.4.1. PCA ordination

Regarding the harpoon point silhouette dataset, two specimens had anomalously high projected PC1 scores, while Early Mesolithic silhouette variation dominated the entire range of the PC2 axis (Fig. 8a). High PC1 scores appeared characteristic of slightly concave back sides and a flat barb side (Fig. 9a). Additionally, the barb side proximal and distal termini are longer on these silhouettes, giving these specimens distinctly pointed tips. Low PC1 scores represented silhouettes with convex proximal segments, blunt tips and relatively flat barb sides, with short basal termini (Fig. 9a). Intuitively, however, the greater width-length ratio characteristic of high PC1 scores was the most obvious difference along this axis.

Specimens assigned low PC2 scores have flat back sides and convex barb sides with long distal termini, creating a pointed tip (Fig. 9b). Along the PC2-axis silhouette shape characteristics included the barb sides re-orienting from convex to flat, to slightly concave, with a concomitant decrease in their width-length ratios. Interestingly, there was a pronounced tendency toward reflective symmetry between the Early Mesolithic specimens that project to positions toward the extreme ends of this axis.

Even though this dataset is small, we noted specimens from spatio-temporal groups had different distributions along this axis, potentially reflecting differences in time and/or space. However, the two PC1 outliers suggested these silhouettes differed from a mechanical perspective and the curious reflective properties of the PC2 eigenvector ordination indicated an important, and previously unidentified, aspect of shape variation is included in silhouette shape.

3.4.2. CVA ordination

Our CVA found no statistically significant set of linear axes that achieved group separation for the harpoon point silhouettes (Fig. 8b, Table 1). There are, however, some additional results worth noting. Early Mesolithic silhouettes were less dispersed in the CV1 vs CV2 space with average scores, while Middle and Late Mesolithic specimens being more scattered. Thus, the Early Mesolithic specimens in our data appeared to have had tendency toward more restricted patterns of shape variation. The CV1 and CV2 shape models show that our Early Mesolithic specimens exhibit small width-to-length ratios, flat back sides, and flat proximal parts with long distal termini on their barb-sides (Fig. 9c, 9d). Once again, the second eigenvector (CV2) revealed reflective symmetry. However, here Middle and Late Mesolithic specimens dominated the along-axis shape space. Also, despite being represented by only two specimens, Late Mesolithic silhouettes from the Eastern circum-Baltic Sea region and Early Mesolithic silhouettes projected to positions within the same cluster. Hence, the distribution of harpoon silhouette shapes in our sample may indicate the preservation of an older shape convention in that region.

3.4.3. PCA of undated harpoon silhouettes

To better understand, and establish a context for, the PCA and CVA results described above, 111 undated harpoon points were digitized and analyzed alongside the 18 dated specimens. Analysis of this larger dataset revealed that c. 85 percent of specimens exhibit projected PC1 scores between −0.07 and 0.02 (Fig. 8c). All specimens from the dated

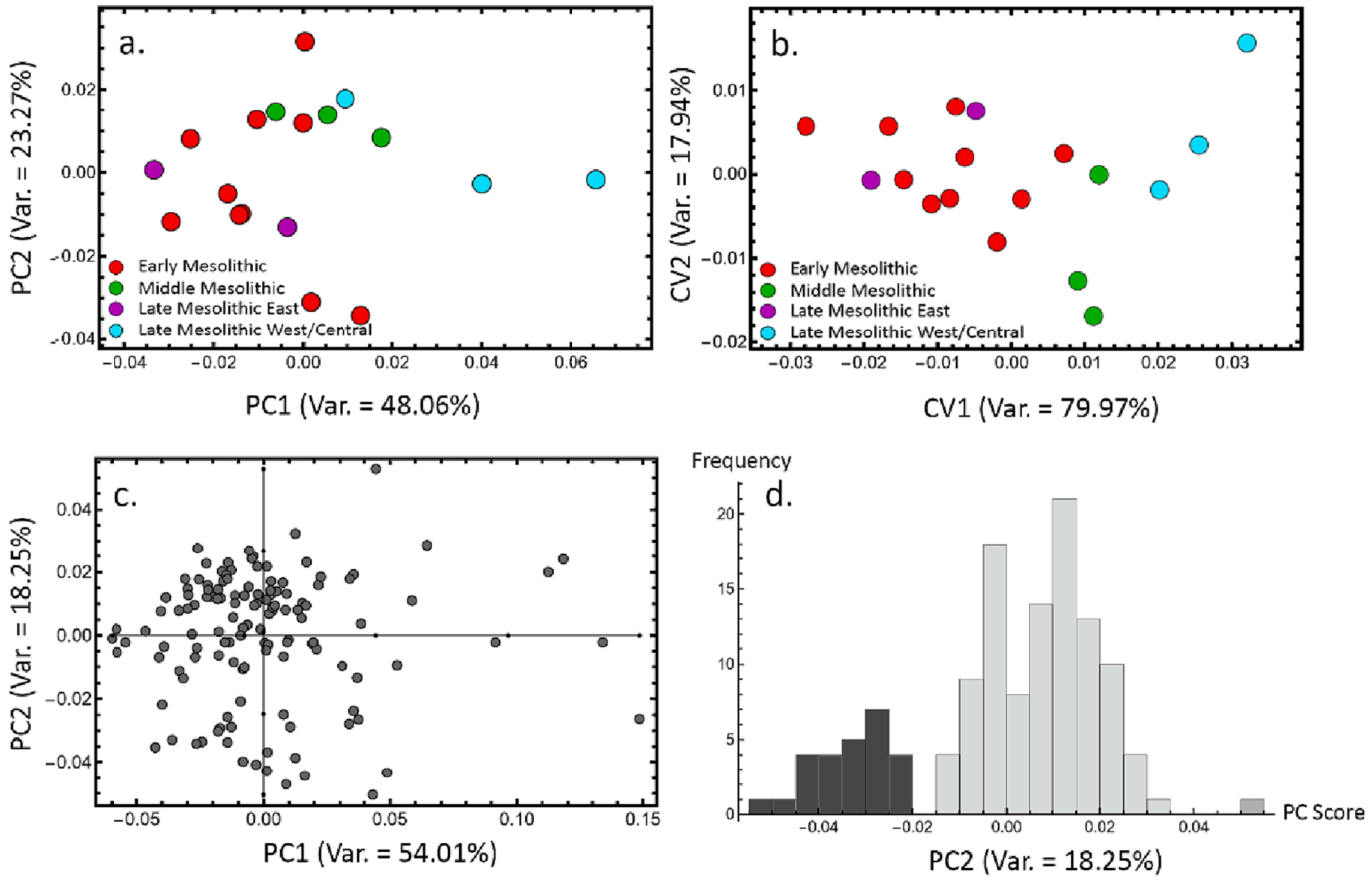


Fig. 8. PCA (a) and CVA (b) ordinations of dated harpoon silhouettes reveal similar distributional patterns. The CVA result (b), shows separation of spatiotemporal groups with exception for the Early Mesolithic and Late Mesolithic East specimens. The PC1 vs PC2 species of undated harpoon silhouettes (c) shows distribution patterns that correspond to the tendencies in the PCA space of dated specimens (a). The distribution of undated silhouettes along PC2 (d) seems organized into two groups. The single outlier, on the axis right end, is an undated specimen.

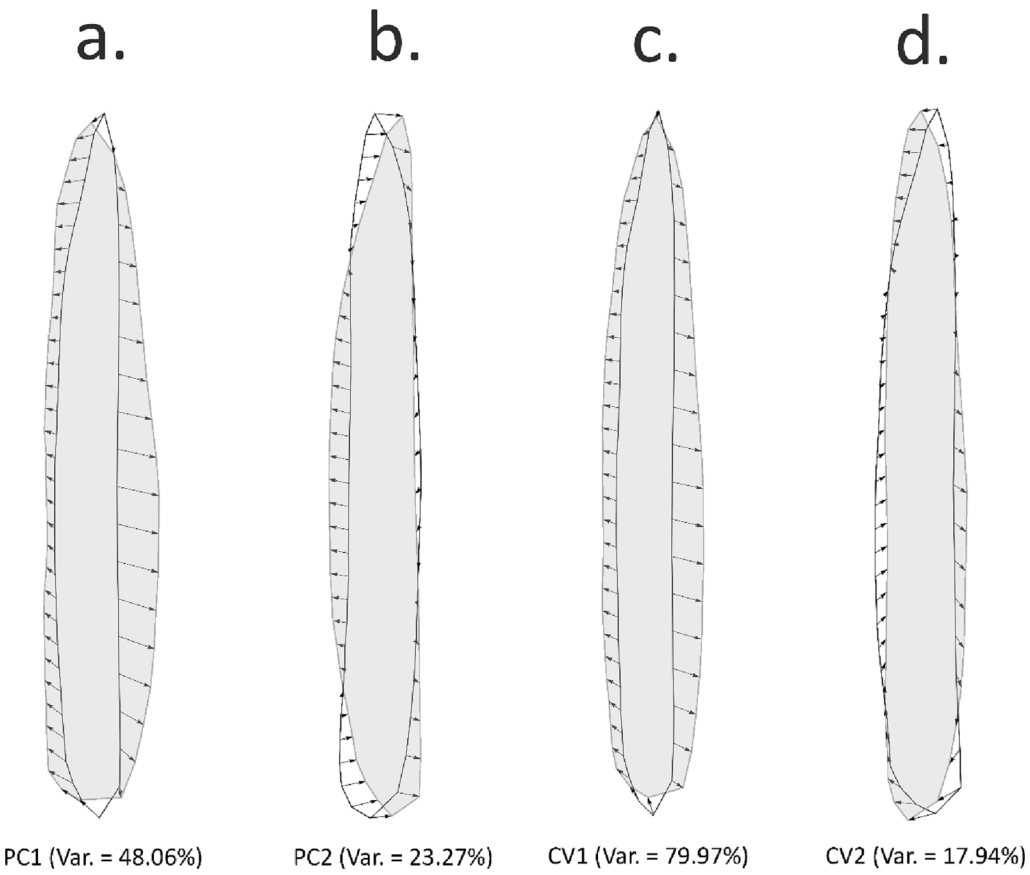


Fig. 9. Models represent shape contrasts along the PC (a, b) and CV (c, d) axes for the spatiotemporally assigned harpoon silhouettes. Shading and arrow conventions as in Fig. 4.

dataset, except the two that had anomalously high PC1 scores, belonged to this group, while the two outliers belonged to a scattered minority characterized by scores between 0.02 and 0.15. Here, shape differences were accentuated, with low scores representing barb shapes with flat back and barb sides and small width-to-length ratios, while high scores represent shapes with convex back and barb sides and large width-to-length ratios (Fig. 10a). Consequently, our analysis of undated specimens supported our interpretation that our dated harpoon-point silhouette results reflect application of a consistent set of design principles, while the presence of shape outliers suggested inclusion of a subclass (or possibly several subclasses) with different design properties and so, potentially, different use(s) or roles.

Within this larger dataset, two shape groups were present along PC2 (Fig. 8d, 10b). Additionally, as with PC2 shape contrasts of the dated dataset, the undated analysis PC2 shape contrasts revealed reflective symmetry. Low PC2 scores represent barbs with convex backs and flat barb sides, while high scores typify barbs with flat backs and convex barb sides (Fig. 10b). Mid-range scores represent silhouettes with flat back and barb sides.

Since the two silhouette PC2 clusters seem to represent reflective symmetry and were not aligned with the archaeological groups, some other influential variable must be affecting this shape-space ordination. Logically, before the creation of barbs and other sub-structures, the reflective symmetry indicates blanks for both silhouette clusters would have been affected by similar shape constraints. Thus, reflectional symmetry seems to be a remnant of raw material shape (c.f., Andersen and Vang Petersen, 2009: 10f; David et al., 2022: 10).

Additionally, positions of dated specimens along the PC2 axis indicated that Early Mesolithic shape variability dominated this shape eigenvector. The Early Mesolithic harpoon points in our dataset were mainly made from ungulate long bones (see Supplementary Materials Table 1). Therefore, it appears that alignment of harpoon point blanks before grooving, in relation to the curvature of the osseous material – in particular bone – dictated a substantial component of pooled-shape variation (c. 18.25% percent) in our larger harpoon point silhouette dataset (Fig. 11).

4. Discussion and conclusions

4.1. Shape convention in harpoon points

Our results showed that a GM characteization of harpoon barbs from the circum-Baltic Sea region, in combination with PCA and CVA can confirm the presence of distinct geographical and chronological shapes in a priori-defined groups. Since groups defined in time and space are of interest to archaeologists, the fact that barb-shape differences appear to distinguish groups in this region may indicate the presence of shape convention(s). Even though the chronologic and geographic group mean barb shapes exhibit statistically significant differences, some overlaps were recorded in group shape ranges. This is not unexpected insofar as, in our study, we focused only on one aspect of barb shape – the two-dimensional outline. Observed overlaps might represent spatiotemporal trajectories of changes in this shape category. Our CVA results support the presence of such trajectories since barbs assigned to Central and Middle Baltic geographic groups were distributed “centrally on/in the middle of” the CVA ordination plots. Regardless, our results are consistent with the presence of shape conventions and provide the first indication that shape-specific spatiotemporal trajectories existed in the circum-Baltic Sea region. Future studies could test these trajectories using different morphometric measures or other lines of evidence and determine whether there are historical/genetic relationship between specific spatiotemporal groups.

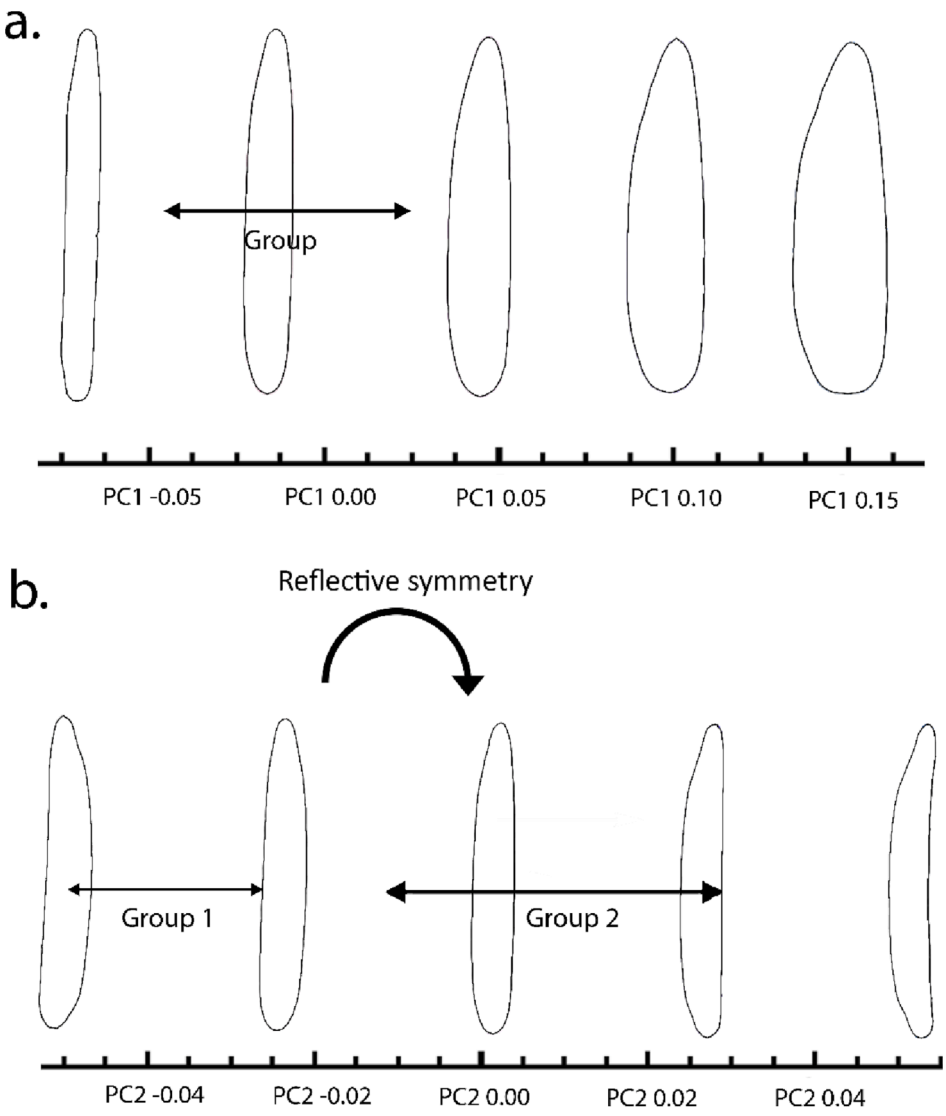


Fig. 10. a. PCA axis models of undated harpoon silhouettes reveal shape groups unrelated to spatiotemporal assignments. cirka 85 percent of specimens have below average to small width-length ratios, while outliers have different ratios. b. The undated dataset also reveals two clusters in relation to reflective symmetry.

For the harpoon point silhouette data, CVA was not able to separate shape groups with statistical significance. However, the group with the largest sample size — Early Mesolithic displayed constrained variation trends in the PCA shape-ordination space. Due to our limited harpoon-silhouette sample size, these differences are difficult to interpret from the perspective of shape convention. However, interpretations consistent with such results can be offered in relation to functional constraints.

Previous morphological studies have addressed harpoon shape conventions; in particular, form variation and form development from the Early to the Late Mesolithic (Andersen, 1971; Larsson, 1999; Andersen and Vang Petersen, 2009; Galiński, 2013; Orłowska and Osipowicz, 2018). Some of these studies have referred to chronological barb-shape differences (e.g., Galiński, 2013). Chronological barb-shape outliers have also been noted (e.g., Orłowska and Osipowicz, 2021). A recent GM analysis of Late Palaeolithic and Early Mesolithic barbed points has also shown that barb-shape disparity decreases during the Early Mesolithic, suggesting this might be related to an increase in population size (Tsirintoulaki et al., 2023). Our results confirm that barb shape can be used to reveal chronological artifact shape differences that may reflect fabrication convention and reaffirms the use of harpoon barbs as a classification characteristic (c.f., Galiński, 2013). Additionally, our results suggest that at least three chronological shape groups can be defined precisely (via their outline geometries) and that specimens be classified reliably according to those definitions.

General differences between osseous point tool-kits from the western and eastern circum-Baltic Sea region have been described previously (e.g., Verhart, 1990; Galiński, 2013) and osseous "techno-complexes" along a northeast-southwest axis defined based on craft-technology analyses (e.g., David, 2009; Bergsvik and David, 2015; David and Kjällquist, 2018). Furthermore, division of the circum-Baltic area into eastern and western regions has been proposed as a result of some harpoon point typological studies. For example, the distribution of certain harpoon point types (Andersen, 1996) and harpoon point-base types (Andersen and Vang Petersen, 2009) conform to a boundary placed between the Danish isles and the rest of the Baltic Sea. However, barb shape differences between the Early Mesolithic western and eastern parts of the circum-Baltic Sea region, along with the long-term geographical barb shape differences evident in our results, have, to the best of our knowledge, never been demonstrated before. Moreover, compared to earlier approaches, our 2D shape-analysis approach offers a useful way to identify and test geographical and temporal complex weapon point shape differences quantitatively, at the level of individual specimens.



Fig. 11. Curvature in original specimens. a. Group 1: convex back (Rönneholm LUHM 17532harpoon point); b. harpoon point silhouette Rönneholm LUHM 17532; c. Group 2: convex barb sides (Vejlasjön harpoon point); d. harpoon point silhouette Vejlasjön. Photographed at the Lund University Historical Museum and published with permission.

4.2. Functional constraints on harpoon point shape

Our results demonstrate that, through the application of GM techniques to both barbs and harpoon point silhouettes, patterns of variation related to functional constraints, raw material and usage can be revealed. In our multiple-barb dataset, our PC1 ordination revealed variation that can be interpreted as being related to use-wear. Previous GM studies have shown that such factors can effect the placement of specimen shapes within PCA-based shape spaces (e.g., de Azevedo et al., 2014; Suárez and Cardillo, 2019). Alignment of the PC2 eigenvector for that dataset, however, largely reflected chronological group differences. This result suggests the possibility of evaluating the effect of shape convention on functional constraints or vice versa. For our harpoon-point silhouettes we were also able to explore variation related to functional constraints and raw materials. Overall weapon-system structure would be expected to accommodate functional constraints that differ from those of sub-structures. Harpoon-point shape (i.e., the silhouette) is subject to a range of functional constraints such as piercing ability, tissue displacement ability and delivery system (e.g., the shaft or the spear-thrower) while a single barb would be subject to fewer functional constraints (i.e., retention of the harpoon in the target). In practice, a harpoon point with an insufficient form would not be able to function as part of a specific weapon-delivery system, in a specific environment and/or against a specific target.

The influence of these demands is reflected in our silhouette-analysis results. For instance, our silhouette shape PCA ordinations exhibit more outliers and clusters than our barb shape PCA ordinations. Previous GM analyses have demonstrated that PCA can be used to explore functional variation. For example, the shape of a ship hull has been shown to be a good indicator of main function (Dhoop et al., 2020) and studies of weapon points have used PCA to address both delivery-system constraints (Doyon, 2019) and functional variation (e.g., Serwatka and Riede, 2016; Serwatka, 2018). While, on the one hand, our PC1 shape ordination of combined dated and undated harpoon points revealed the presence of shape outliers, our PC2 ordination revealed the influence of raw materials — primarily ungulate long bone — on harpoon point silhouette shape. But even though harpoon silhouette shape appears to have been, to a certain extent, determined by raw material, the choice of aligning different parts of the harpoon point in relation to raw material shape would have affected the strength and the mechanical properties of the overall harpoon point (c.f., David et al., 2022). The shape clusters revealed by our analysis suggest that certain ways of shaping the raw

material were preferred. Thus, a 2D GM approach can reveal how raw material constraints were engaged by the persons who crafted and used these objects to ensure their effectiveness.

A review of archaeological barbed point studies reveals that discussions of functionality are important to such investigations, even if the aims of the study are typological primarily. Above all, archaeologists have been preoccupied with questions of how to categorize Paleolithic and Mesolithic barbed points functionally. Even though researchers who study structurally simpler points experience challenges associating projectiles with delivery systems (e.g., Christenson, 1986; Hughes, 1998; Iovita et al., 2016), the complex nature of barbed points raises more issues. Barbed points could have been parts of composite weapons, such as leisters, or single-component systems with a loose or a tight shaft attachment (i.e., a harpoon or a spear). To deal with functional definitions, archaeologists have used ethnographic size ratios of both substructures and structures to categorize points (e.g., Weniger, 1995, 2000). Alternatively, researchers have approached the dilemma of functional definition by voluntarily omitting functional roles. This is reflected in classifications that include all types of osseous points (e.g., Clark, 1936:115-124) or studies that include all types of barbed points (e.g., Tsirintoulaki et al., 2023).

Ethnographical and historical analogies illuminate how archaeological harpoon points have been used (e.g., Clark, 1936: 115ff; Christensen et al., 2016; Piličiauskas et al., 2020; Vang Petersen, 2009; Weniger, 2000; Hartz et al., 2020; Pétillon, 2009: 10ff). Rather than guiding archaeological interpretations though, these examples illustrate functional diversity and flexibility (c.f., Ickerodt, 2013). For example, at least one ethnographic investigation revealed that the functional role of a barbed point can be changed during a hunting episode from harpoon point to spear point and vice versa, by tying the point to the shaft in different ways (Christensen et al., 2016). Consequently, it is difficult to define and/or assign particular functional roles to particular complex weapon point structures by use of analogy. In view of these difficulties, a geometry-based approach offers a way to test for the presence and/or operation of functional constrains through quantitative comparisons, definitions and categorizations that are tied only to the geometries the artifact structures exhibit. The interpretation of structured patterns of shape variation, shape differences between a priori defined groups, etc, can be enhanced greatly by converting the projected point locations in mathematically abstract ordination spaces back into diagrams of the shapes/forms that exist mathematically at any location within such spaces. By creating proxies (the harpoon point silhouettes) from complex weapon points, we were able to identify clusters and outliers in geometrically defined ordination spaces that can be used to place specimens into categories objectively, based on the geometries they exhibit. The issue of whether these geometric patterns are associated deterministically with other sorts of archaeological observations/data can then be evaluated statistically, based on the amount and quality of those observations/data. By applying the quantitatively geometric analysis of shape and form (e.g., GM, computer modelling, machine learning), the power of this approach can enable a shift in focus from qualitative perception to more precise formulations regarding what is meant by shape convention and functional constraints, as well as how such hypotheses can be tested.

4.3. Archaeological potential of geometry-based approaches

The quantitative nature of GM analysis identifies it as a means through which to approach to specific archaeological research questions. Quantitative geometric analyses can not only provide a more precise and valid categorizations than qualitative typological assessments (e.g., MacLeod and Nash, 2021), these methods can also abstract information for specific research purposes. Thus, quantitative geometric analysis represents a generic approach to the analysis of artifact morphologies from which valid and reproducible knowledge can be obtained. When applied to a sufficiently large sample, this approach offers the opportunity to quantify the aspects of single specimen shapes; even those that are incomplete or damaged. Geometric abstraction also has the potential to make highly sensitive characterizations of shape a parameter to be compared to other archaeologically important parameters along the same quantitative lines.

To understand the wider implications of our evaluation of chronological and geographical pre-defined groups, along with possible shape trajectories, shape groups should also be related to events and variations supported by the geological, paleoclimatic and/or archaeological record (c.f., Buchanan et al., 2014). For example, long-term environmental changes, like the Baltic Sea Basin changing from a lake (Ancylus) into a sea (Littorina), the related disappearance of Doggerland and the Öresund land bridges, and shorter climatic events such as the 8.2 cal BP cold event, are specific incidents that the producers and users of harpoons would have been required to adapt to, with potential effects on harpoon point shape development as a result. Shape variation and/or development could also be compared to the spread of other artifacts, technology, populations and/or biota. Above all, archaeological artifact shape groups and trajectories can be compared to the results of osseous technology analyses. These analyses have demonstrated the existence of different Early Mesolithic bone “techno-complexes” and a successive replacement of a Northwestern Techno-complex by a Northeastern Techno-complex (e.g., David, 2009; Bergsvik and David, 2015; David and Kjällquist, 2018). Barb shape trajectories could be directly or indirectly related to such techno-complexes and raw material constraints identified by technological analyses (c.f, David et al., 2022). As a result, structurally complex weapon points may be able to be transformed from a source of conceptual perplexity and nomenclatural confusion into a rich source of archaeological information.

Our GM analyses were performed on a large dataset with low resolution. Geometrical analyses can be made both more precise and more comprehensive than our exemplar investigation. Homogenous imaging programs would enable machine-learning classifications, which have been shown to produce valid and precise morphological groupings (MacLeod and Kolska Horwitz, 2020; MacLeod et al., 2021, 2022). With 3D-models, detailed performance data could also be retrieved (e.g., Lundström, 2019). Regardless, the assembly of larger dated artifact samples is now critically necessary if the full power of geometry-based approaches is to be brought to bear on the understanding of complex archaeological weapon points.

CRediT authorship contribution statement

Fredrik Lundström: Conceptualization, Investigation, Writing – original draft, Visualization, Formal analysis. **Norman MacLeod:** Conceptualization, Methodology, Software, Verification, Data curation, Writing – review & editing, Supervision. **Sven Isaksson:** Conceptualization, Writing – review & editing, Supervision. **Aikaterini Glykou:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2023.104148. Data analysis routines to this article can be found online at https://doi.org/10.5281/zenodo.8263170.

References

Alley, R.B., Ágústsdóttir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. Quat. Sci. Rev. 24, 1123–1149. https://doi.org/10.1016/j.quascirev.2004.12.004.

Andersen, S.H., 1996. Ertebølleharpuner og spækhuggertænder. Aspekter af marin fangst i Ertebølletid. Kuml 40 (40), 45–100.

Andersen, S.H., 1975. Nye harpunfund. Nye harpunfund. Kuml 24 (24), 11–28.

Andersen, S.H., 1971. Ertebøllekulturens harpuner. Ertebøllekulturens harpuner. Kuml 21 (21), 73–126.

Andersen, S.H., Vang Petersen, P.A., 2009. Maglemosekulturens stortandede harpuner. Aarbøger Nord. Oldkynd. Og Hist. 2006, 7–41.

Anderson, M.J., Willis, T.J., 2003. Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology. Ecology 84 (2), 511–525.

Bergsvik, K., David, É., 2015. Crafting Bone Tools in Mesolithic Norway: A Regional Eastern-Related Know-How. Eur. J. Archaeol. 18, 190–221. https://doi.org/10.1179/1461957114Y.0000000073.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A., Lohne, Ø., 2003. Record-breaking height for 8000-year-old tsunami in the North Atlantic. Eos Trans. Am. Geophys. Union 84, 289–293. https://doi.org/10.1029/2003EO310001.

Buchanan, B., O'Brien, M., Collard, M., 2014. Continent-wide or region-specific? A geometric morphometrics-based assessment of variation in Clovis point shape. Archaeol. Anthropol. Sci. 6, 145–162. https://doi.org/10.1007/s12520-013-0168-x.

Buchanan, B., Collard, M., O'Brien, M.J., 2020. Geometric Morphometric Analyses Support Incorporating the Goshen Point Type into Plainview. Am. Antiq. 85, 171–181. https://doi.org/10.1017/aaq.2019.89.

Campbell, N.A., Atchley, W.R., 1981. The Geometry of Canonical Variate Analysis. Syst. Zool. 30, 268–280. https://doi.org/10.2307/2413249.

Chacón, M.G., Détroit, F., Coudenneau, A., Moncel, M.-H., Bicho, N., 2016. Morphometric Assessment of Convergent Tool Technology and Function during the Early Middle Palaeolithic: The Case of Payre. France. PLOS ONE 11 (5). https://doi.org/10.1371/journal.pone.0155316.

Charlin, J., González-José, R., 2012. Size and Shape Variation in Late Holocene Projectile Points of Southern Patagonia: A Geometric Morphometric Study. Am. Antiq. 77, 221–242. https://doi.org/10.7183/0002-7316.77.2.221.

Christensen, M., Legoupil, D., Pétillon, J.-M., 2016. Hunter-Gatherers of the Old and New Worlds: Morphological and Functional Comparisons of Osseous Projectile Points. In: Langley, M.C. (Ed.), Osseous Projectile Weaponry: Towards an Understanding of Pleistocene Cultural Variability, Vertebrate Paleobiology and Paleoanthropology. Springer, Netherlands, Dordrecht, pp. 237–252. https://doi.org/10.1007/978-94-024-0899-7_16.

Christenson, A.L., 1986. Projectile Point Size and Projectile Aerodynamics: An Exploratory Study. Plains Anthropol. 31, 109–128. https://doi.org/10.1080/2052546.1986.11909324.

Clark, J.G.D., 1936. The Mesolithic Settlement of Northern Europe. Cambridge University Press.

Cooke, S.B., Terhune, C.E., 2015. Form, Function, and Geometric Morphometrics. Anat. Rec. 298, 5–28. https://doi.org/10.1002/ar.23065.

David, É., 2009. Show me how you make your hunting equipment and i will tell you where you come from: Technical traditions, an efficient means of characterizing cultural identities. Mesolith. Horiz. 362–367.

David, É., Kjällquist, M., 2018. Transmission of crafting traditions in the Mesolithic: A study of worked material from Norje Sunnansund, Sweden. In: Knutson, K., Knutson, H., Apel, J., Glørstad, H. (Eds.), Technology of early settlement in Northern Europe: Transmission of knowledge and culture. Sheffield, pp. 231–276.

David, É., Sørensen, L., Petersen, P., 2022. How Bone Technology points to Cultural Lineages in Prehistory? New Insights from Danish Late-and Post-Glacial Weapons' Heads. Open Access J. Archaeol. Anthropol. 3. https://doi.org/10.33552/OAJAA.2022.03.000562.

Eren, M.I., Buchanan, B., O'Brien, M.J., 2015. Social learning and technological evolution during the Clovis colonization of the New World. J. Hum. Evol. 80, 159–170. https://doi.org/10.1016/j.jhevol.2015.01.002.

de Azevedo, S., Charlin, J., González-José, R., 2014. Identifying design and reduction effects on lithic projectile point shapes. J. Archaeol. Sci. 41, 297–307. https://doi.org/10.1016/j.jas.2013.08.013.

Dhoop, T., Stark, S., Olaberria, J.-P., Whitewright, J., 2020. Quantifying Ship Shape in Archaeology: Evaluating 3D Geometric Morphometrics. Int. J. Naut. Archaeol. 49, 49–64. https://doi.org/10.1111/1095-9270.12413.

Doyon, L., 2019. On the shape of things: A geometric morphometrics approach to investigate Aurignacian group membership. J. Archaeol. Sci. 101, 99–114. https://doi.org/10.1016/j.jas.2018.11.009.

Figueirido, B., MacLeod, N., Krieger, J., De Renzi, M., Pérez-Claros, J., Palmqvist, P., 2011. Constraint and adaptation in the evolution of carnivoran skull shape. Paleobiology 37, 490–518. https://doi.org/10.2307/23014735.

Fox, A.N., 2015. A study of Late Woodland projectile point typology in New York using elliptical Fourier outline analysis. J. Archaeol. Sci. Rep. 4, 501–509. https://doi.org/10.1016/j.jasrep.2015.10.022.

Galiński, T., 2013. Typological, chronological and cultural verification of Pleistocene and early Holocene bone and antler harpoons and points from the southern Baltic zone. Przegląd Archeol. 61, 93–144.

Gummesson, S., Molin, F., 2020. Points of bone and antler from the Late Mesolithic settlement in Motala, eastern central Sweden. In: Groß, D., Jantzen, D., Lübke, H., Meadows, J. (Ed.), *Working at the Sharp End: From Bone and Antler to Early Mesolithic Life in Northern Europe*. Untersuchungen und Materialien zur Steinzeit in Schleswig-Holstein und im Ostseeraum 10. pp. 263–287.

Hartz, S., Lübke, H., Groß, D., Jantzen, D., Lübke, H., Meadows, J., 2020. Early Mesolithic bone points from Schleswig-Holstein. In: Groß, D., Jantzen, D., Lübke, H., Meadows, J. (Ed.), *Working at the Sharp End: From Bone and Antler to Early Mesolithic Life in Northern Europe*. Untersuchungen und Materialien zur Steinzeit in Schleswig-Holstein und im Ostseeraum 10, pp. 203–238.

Hughes, S.S., 1998. Getting to the point: Evolutionary change in prehistoric weaponry. J. Archaeol. Method Theory 5, 345–408. https://doi.org/10.1007/BF02428421.

Ickerodt, U., 2013. Barbed points through time – A hunting weapon between ethnoarchaeological argumentation and functional analysis. In: Grimm, O., Schmölcke, U. (Eds.), *Hunting in northern Europe until 1500 AD Old Traditions and regional developments, continental sources and continental influences*. Wachholtz Verlag, Neumünster, pp. 113–145.

Ingold, T., 2000. The Perception of the Environment: Essays on Livelihood, Dwelling and Skill. Routledge, London.

Iovita, R., Schönekeß, H., Gaudzinski-Windheuser, S., Jäger, F., 2016. Identifying Weapon Delivery Systems Using Macrofracture Analysis and Fracture Propagation Velocity: A Controlled Experiment. In: Iovita, R., Sano, K. (Eds.), *Multidisciplinary Approaches to the Study of Stone Age Weaponry*. Vertebrate Paleobiology and Paleoanthropology. Springer Netherlands, Dordrecht, pp. 13–27.

Kelly, R.L., 2013. The Lifeways of Hunter-Gatherers: The Foraging Spectrum. Cambridge University Press, Cambridge.

Kozłowski, J.K., Kozłowski, S.K., 1975. Pradzieje Europy od XL do IV tysiąclecia p.n.e. Państ. Wydaw. Naukowe, Warszawa.

Kozłowski, J.K., Kozłowski, S.K., 1977. Epoka kamienia na ziemiach polskich. Państ. Wydaw, Naukowe.

Larsson, L., 1999. From the depth of the sea: a Mesolithic harpoon from the Baltic Sea. Den Bogen SpannenFestschrift Für Bernhard Gramsch Zum 65 Geburstag. Beiträge zur Ur- und Frühgeschichte Mitteleuropas 1999, 169–175.

Lundström, F., 2019. Secrets of the Spearhead : Developing Continuum Mechanical Simulations and Organic Residue Analysis for the Study of Scandinavian Flint Spearhead Functionality. MA-thesis.

Lycett, S.J., von Cramon-Taubadel, N., Foley, R.A., 2006. A crossbeam co-ordinate caliper for the morphometric analysis of lithic nuclei: a description, test and empirical examples of application. J. Archaeol. Sci. 33, 847–861. https://doi.org/10.1016/j.jas.2005.10.014.

MacLeod, N., 1999. Generalizing and extending the eigenshape method of shape space visualization and analysis. Paleobiology 25, 107–138. https://doi.org/10.1666/0094-8373-25.1.107.

MacLeod, N. (Ed.), 2007. *Automated Taxon Identification in Systematics: Theory, Approaches and Applications*. CRC Press, Boca Raton.

MacLeod, N., 2009. Form & shape models. Palaeontol. Assoc. Newsl. 72, 14–27.

MacLeod, N., 2018. The quantitative assessment of archaeological artifact groups: Beyond geometric morphometrics. Quat. Sci. Rev. 201, 319–348. https://doi.org/10.1016/j.quascirev.2018.08.024.

MacLeod, N., Canty, R., Polaszek, A., 2021. Morphology-based identification of bemisia tabaci cryptic species puparia via embedded group-contrast convolution neural network analysis. Syst. Biol. 71, 1095–1109. https://doi.org/10.1093/sysbio/syab098.

MacLeod, N., Kolska Horwitz, L., 2020. Machine-learning strategies for testing patterns of morphological variation in small samples: sexual dimorphism in gray wolf (Canis lupus) crania. BMC Biol. 18, 113. https://doi.org/10.1186/s12915-020-00832-1.

MacLeod, N., Nash, B., 2021. Ford's Gamma-Gamma Village Simulation Revisited: Highlighting the Need for a New Middle-Range Theory of Archaeological Types1. Archaeometry 63, 1081–1104. https://doi.org/10.1111/arcm.12661.

MacLeod, N., Price, B., Stevens, Z., 2022. What you sample is what you get: ecomorphological variation in Trithemis (Odonata, Libellulidae) dragonfly wings reconsidered. BMC Ecol. Evol. 22, 43. https://doi.org/10.1186/s12862-022-01978-y.

Manly, B., F, J., Navarro Alberto, J., A., 2017. *Multivariate Statistical Methods: A Primer*, Fourth Edition. Routledge CRC Press. Abingdon-on-Thames.

Marrama, G., Kriwet, J., 2017. Principal component and discriminant analyses as powerful tools to support taxonomic identification and their use for functional and phylogenetic signal detection of isolated fossil shark teeth. PLoS One 12, e0188806–e. https://doi:10.1371/journal.pone.0188806.

Matzig, D.N., Hussain, S.T., Riede, F., 2021. Design Space Constraints and the Cultural Taxonomy of European Final Palaeolithic Large Tanged Points: A Comparison of Typological, Landmark-Based and Whole-Outline Geometric Morphometric Approaches. J. Paleolit. Archaeol. 4, 27. https://doi.org/10.1007/s41982-021-00097-2.

Orłowska, J., Osipowicz, G., 2021. Accuracy of the typological classifications of the Late Glacial and Early Holocene osseous projectile points according to the new AMS dates of selected artifacts from Poland. Archaeol. Anthropol. Sci. 14, 8. https://doi.org/10.1007/s12520-021-01483-1.

Orłowska, J., Osipowicz, G., 2018. Optic observations on osseous uniserial harpoon heads from the Polish Lowland as an element of discussion about their chronological affiliation. Quaternary International 472, 3–12.

Oswalt, W., H. 1976. *An Anthropological Analysis of Food-getting Technology*. Wiley. Hoboken.

Peres-Neto, P., Jackson, D., Somers, K., 2005. How Many Principal Components? Stopping Rules for Determining the Number of Non-Trivial Axes Revisited. Comput. Stat. Data Anal. 49, 974–997. https://doi.org/10.1016/j.csda.2004.06.015.

Pétillon, J.-M., 2009. What are these barbs for? Preliminary reflections on the function of the Upper Magdalenian barbed weapon tips.P@lethnologie, 2008, 1. pp. 66–97.

Pettitt, P., Rowley-Conwy, P., Montgomery, J., Richards, M., 2017. A cold case closed. New light on the life and death of the Lateglacial elk from Poulton-le- Fylde (Lancashire, UK): Neue Erkenntnisse zu einem bisher ungelösten Fall: Das Leben und Sterben des spätglazialen Elchs von Poulton-le-Fylde (Lancashire, GB). Quartär – Int. Jahrb. Zur Erforsch. Eiszeitalt. Steinzeit 64, 179–202. https://doi.org/10.7485/QU64_8.

Piličiauskas, G., Matiukas, A., Peseckas, K., Mažeika, J., Osipowicz, G., Piličiauskienė, G., Rannamäe, E., Pranckėnaitė, E., Vengalis, R., Pilkauskas, M., 2020. Fishing history of the East Baltic during the Holocene according to underwater multiperiod riverine site Kaltanėnai, northeastern Lithuania. Archaeol. Anthropol. Sci. 12, 279. https://doi.org/10.1007/s12520-020-01233-9.

Rohlf, F.J., Slice, D., 1990. Extensions of the Procrustes Method for the Optimal Superimposition of Landmarks. Syst. Biol. 39, 40–59. https://doi.org/10.2307/2992207.

Salili-James, A., Mackay, A., Rodriguez-Alvarez, E., Rodriguez-Perez, D., Mannack, T., Rawlings, T.A., Palmer, A.R., Todd, J., Riutta, T.E., Macinnis-Ng, C., Han, Z., Davies, M., Thorpe, Z., Marsland, S., Leroi, A.M., 2022. Classifying organisms and artefacts by their outline shapes. J. R. Soc. Interface 19, 20220493. https://doi.org/10.1098/rsif.2022.0493.

Serwatka, K., 2018. What's your point? Flexible projectile weapon system in the Central European Final Palaeolithic. The case of Swiderian points. J. Archaeol. Sci. Rep. 17, 263–278. https://doi.org/10.1016/j.jasrep.2017.10.048.

Serwatka, K., Riede, F., 2016. 2D geometric morphometric analysis casts doubt on the validity of large tanged points as cultural markers in the European Final Palaeolithic. J. Archaeol. Sci. Rep. 9, 150–159. https://doi.org/10.1016/j.jasrep.2016.07.018.

Sholts, S.B., Gingerich, J.A.M., Schlager, S., Stanford, D.J., Wärmländer, S.K.T.S., Petraglia, M.D., 2017. Tracing social interactions in Pleistocene North America via 3D model analysis of stone tool asymmetry. PLOS One 12 (7), e0179933.

Sievwright, H., Macleod, N., 2012. Eigensurface analysis, ecology, and modelling of morphological adaptation in the falconiform humerus (Falconiformes: Aves). Zool. J. Linn. Soc. 165, 390–419. https://doi.org/10.1111/j.1096-3642.2012.00818.x.

Simon, H.A., 1991. The Architecture of Complexity. In: Klir, G.J. (Ed.), *Facets of Systems Science, International Federation for Systems Research International Series on Systems Science and Engineering*. Springer US, Boston, MA, pp. 457–476.

Smeyatsky, I., 2014. Stylistic Variation in Later Stone Age Tanged Arrowheads: a Pilot Study Using Geomet-ric Morphometrics. ARCHAEOLOGY, University of Witwatersrand, Johannesburg, 49. Thesis.

Smith, H.L., Jennings, T.A., Smallwood, A.M., 2021. Do early Paleoindian point blades carry culturally significant shape information? Modules versus complete points using geometric morphometrics. J. Archaeol. Sci. Rep. 40, 103245 https://doi.org/10.1016/j.jasrep.2021.103245.

Smith, H.L., Reid, A.E., 2022. Evaluating the Fluted Points from Spring Lake, Texas: A Geometric Morphometric Shape Analysis of Clovis Affinity. PaleoAmerica 8, 340–351. https://doi.org/10.1080/20555563.2022.2090728.

Stattegger, K., Leszczyńska, K., 2023. Rapid sea-level rise during the first phase of the Littorina transgression in the western Baltic Sea. Oceanologia 65, 202–210. https://doi.org/10.1016/j.oceano.2022.05.001.

Suárez, R., Cardillo, M., 2019. Life history or stylistic variation? A geometric morphometric method for evaluation of Fishtail point variability. J. Archaeol. Sci. Rep. 27, 101997 https://doi.org/10.1016/j.jasrep.2019.101997.

Thom, R., 1975. *Structural Stability and Morphogenesis: An Outline of a General Theory of Models*. Benjamin, W. A, Reading.

Thulman, D.K., 2012. Discriminating Paleoindian point types from Florida using landmark geometric morphometrics. J. Archaeol. Sci. 39, 1599–1607. https://doi.org/10.1016/j.jas.2012.01.004.

Tsirintoulaki, K., Matzig, D.N., Riede, F., 2023. A 2D Geometric Morphometric Assessment of Chrono-Cultural Trends in Osseous Barbed Points of the European Final Palaeolithic and Early Mesolithic. Open Archaeol. 9 https://doi.org/10.1515/opar-2022-0276.

Vang Petersen, P.A., 2009. Stortandede harpuner - og jagt på hjortevildt til vands. Aarbøger Nord. Oldkynd. Og Hist. 2005, 43–53.

Vankina, L., 1999. The collection of Stone Age bone and antler artefacts from Lake Lubāna: catalogue. Latvijas Vēstures Muzeja raksti. N.I.M.S, Rīga.

Verhart, L., 1990. Stone Age Bone and Antler Points as Indicators for Social Territories in the European Mesolithic. In: Vermeersch, P.M., Van Peer, P. (Eds.), *Contributions to the Mesolithic in Europe. Leuven*, pp. 139–151.

Weniger, G.-C., 2000. Magdalenian Barbed Points: Harpoons. Spears and Arrowheads. Anthropol. Prehistoire 111, 79–87.

Weniger, G.-C., 1995. *Widerhakenspitzen des Magdalénien Westeuropas: Ein Vergleich mit ethnohistorischen Jägergruppen Nordamerikas*. Zabern, Phillip Von, Mainz am Rhein.

White, A.A., 2013. Functional and Stylistic Variability in Paleoindian and Early Archaic Projectile Points from Midcontinental North America. North Am. Archaeol. 34, 71. https://doi.org/10.2190/NA.34.1.c. http://baywood.com.