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Abstract

The manufacture of composite projectile technology requires the production and assemblage of tightly fitted parts designed to fulfill a number of distinct functions. Each part combines a number of techno-functional units, and various processes may be responsible for the shape variability of these units. In order to investigate the relative contribution of each process to the overall variability of a projectile implement, one must identify the point of demarcation between its techno-functional units. In the present paper, the concept of shape modularity is introduced to precisely identify this locus. The application of geometric morphometrics and shape modularity to the study of two Aurignacian osseous projectile point types, i.e., split- and massive-based points, reveals interesting patterns. On both types, the maximum width delimits the distal and proximal techno-functional units of these objects. When focusing on the morphometric variability and the geographic distribution of the implements' proximal unit, the eight shapes identified for split-based points are found over vast regions of Europe. On the other hand, the two proximal shapes defined for massive-based points show a pattern of local, or regional, aggregation. These proximal shapes were likely considered fit for hafting and hunting by the prehistoric populations who reproduced them, and they are interpreted as a proxy for the socially shared rules of production that guided the manufacture of these tool

types. They could therefore be used in future studies that aim to identify group membership amongst the Aurignacian metapopulation and the extent of their interactions.

Keywords: Bone technology; Projectile points; Early Upper Palaeolithic; Europe; Shape modularity

Highlights

- A geometric morphometric method is described to analyze tools with simple outlines
- Shape modularity test is used to identify techno-functional components of an object
- For split-based points, eight distinct proximal shapes are found over vast regions
- The two proximal shapes identified for massive-based points are locally aggregated
- The proximal shapes represent a proxy for the socially shared rules of production

Introduction

The Aurignacian is a key technocomplex of the European Early Upper Palaeolithic. Its associated archaeological record is characterized by the co-occurrence of cultural items usually attributed to anatomically modern human behavior (Henshilwood and Marean, 2003; McBrearty and Brooks, 2000), such as the widespread adoption of blade and bladelet technology, the manufacture of bone technology, and the production of art and of a rich symbolic material culture. One aspect of Aurignacian material culture is of particular interest as it plays a central role in the definition of the different phases of the technocomplex. It consists of the projectile points made of antler, bone, and ivory. These elongated armatures with a simple outline are divided into two types, i.e., split- and massive-based points. The presence or absence of a split on the proximal portion, visible from the lateral view of the object, serves as a criterion for their typological categorization (Hahn, 1988a, 1988b). Split-based points are usually associated with Early Aurignacian archaeological contexts (~40-36 ka BP) and massive-based points with the Middle and Later phases of the Aurignacian (~37-32 ka BP).

Previous attempts have failed to identify patterned variation amongst split- and massive-based points (Albrecht et al., 1972; Clément and Leroy-Prost, 1977; Knecht, 1991; Turk, 2002, 2003, 2005). The methodology and the analytical tools selected to study the armatures' shape are two factors at the root of this inconclusive outcome. From a methodological standpoint, the works by Turk (2002, 2003, 2005) focused on the absolute and relative dimensions of massive-based points from Central Europe. This approach allowed him to identify use and resharpening as primary converging processes that produce morphometric variability on the distal portion of the implements, however, it failed to address the shape variability of the proximal portion of these objects. Other researchers investigated variation in both the shape and size of archaeological specimens (Albrecht et al., 1972; Clément and Leroy-Prost, 1977; Knecht, 1991). However, they searched for patterns of variation through the analysis of the implements' general outline in an attempt to identify the specific forms reproduced by the makers of the Aurignacian projectile points. Consequently, the results obtained necessarily conflated a minimum of two sources of variation, i.e., the range of forms of newly manufactured points and the morphometric variability resulting from their utilization. Shape variation in tools could be caused by a variety of processes. Therefore, given the anisotropic properties of osseous material, one cannot assume every portion of a point would be equally affected by these processes (see below).

From an analytical standpoint, with the exception of the works by Turk (2002, 2003, 2005), these studies were carried out prior to, or during, the development of modern landmark-based geometric morphometrics (Bookstein, 1989, 1991, 1996, 1997; Moyers and Bookstein, 1979). The theoretical and methodological advances made in this field of investigation over the last two decades now bring forth new prospects to reassess the morphometric variability of Aurignacian osseous projectile points with the aim of identifying the shapes that were reproduced by the prehistoric populations. In the present paper, the concept of shape modularity (Adams, 2016; Klingenberg, 2008, 2009; Klingenberg and Marugán-Lobón, 2013) is used to analyze the outline of Aurignacian split- and massive-based points from 38 European sites. This concept is useful to identify the point of demarcation between distinct techno-functional units, or components, on the shape of an implement of composite technology. The morphometric variability of each component can then be interpreted as a result of functional and/or stochastic processes in the light of technological and experimental data. Focusing on the component that is mainly affected by stochastic processes allows the identification of eight proximal shapes for split-based points and two proximal shapes for massive-based points. The geographic distribution of these shapes is investigated to assess patterns of regionalization.

Research background

Distinguishing between groups of cultural artefacts constitutes an important goal in archaeological studies. Over the past decade, specialists of lithic technologies have invested much effort in investigating patterned variation in the morphology of stone tools by applying landmark-based geometric morphometrics methods to their studies (e.g., Archer and Braun, 2010; Buchanan et al., 2013; Buchanan and Collard, 2010a, 2010b; Cardillo, 2010; Charlin and González-José, 2012; Costa, 2010; Lycett et al., 2010; Lycett and von Cramon-Taubadel, 2013; MacLeod, 2018; Petřík et al., 2016; Picin et al., 2014; Shott and Trail, 2010; Thulman, 2012). However, borrowing a tool conceived for evolutionary biological studies and applying it to the study of material culture necessarily requires some adaptations. To make sense of the patterned variation of a given tool type, studies on shape variability should be carried out by taking into consideration the relevant technological and experimental data which inform us on the processes that generate variation in material culture. Throughout the present section, Aurignacian osseous projectile points are used as a case study to exemplify how the integration of such technological, experimental, and morphometric data can be achieved. However, the logic outlined below can be adapted to other prehistoric tool types. First, the challenges inherent to applying geometric morphometrics methods to analyze tools with a geometrically simple outline are presented. It is followed by a discussion on the technology of composite projectile to highlight the importance of using the concept of shape modularity to quantitatively identify the point of demarcation between distinct techno-functional units on projectile armatures. Then, experimental data on the use and efficiency of prehistoric projectile technology is reviewed to target the techno-functional unit that is more likely to retain the original shapes reproduced during the manufacture of the points. Finally, the factors causing shape variation are summarized as well as the criteria that allow identifying their respective effect on the archaeological record.

Applying geometric morphometrics methods to the analysis of Aurignacian osseous projectile points constitutes a real challenge given their simple outline and the fragmentary state of most specimens. On the one hand, the simple outline limits the number of Type I landmarks (Bookstein, 1991; Mardia and Dryden, 1989) that can possibly be recorded, i.e., the loci equivalent to anatomical features present on every outline such as the distal tip, the basal end, or the points delimiting the maximum width of the artefact. In most cases, only the latter two landmarks are available, i.e., the two landmarks that are placed on either side of the point of maximum width (see Lycett et al., 2006 for a discussion on the lack of Type I landmarks on archaeological artefacts). However, their position at either end of one of the tool's major axis, i.e., the maximum width, prevents the precise definition of homologous sliding semi-landmarks (Perez et al., 2006) along the outline of the point. On the other hand, given that most specimens are damaged, with distal and/or proximal fractures, it is not possible to accurately estimate the percentage of completeness of a point. Consequently, both semi-landmark methods (Bookstein, 1997) and Fourier transform methods (Haines and Crampton, 2000) cannot be used for simple shape comparison.

Some studies have explored the possibility of digitizing the tool's shape by recording landmark coordinates from a polar grid superimposed on photographs of the artefacts and centered at the intersection of the implements main axes, i.e., the maximum length and width (Archer and Braun, 2010; Lycett et al., 2010; Lycett and von Cramon-Taubadel, 2013). The use of a polar grid ensures the homology of each landmark regardless of variation in the size or the shape of the artefact. This method confers a substantial advantage as it allows the quantification of the amplitude at which a shape varies in any direction from a given centroid. The problem that arises is how variation resulting from the use and repair of an object can be distinguished from the forms originally replicated during its manufacturing process. Such distinction requires a prior understanding of the various constraints inherent to the technological project that led to the production of the tool and the context in which it was used.

The manufacture of composite projectile technology requires the production and assemblage of tightly fitted parts designed to fulfill a number of distinct functions. For instance, the proximal end of a shaft must be shaped to ensure it adequately grips the launching device to allow the proper transfer of projecting forces to the projectile when launched. Meanwhile, the distal end of the shaft must be carved to facilitate the hafting of an armature. It should ideally be streamlined and smoothed in order to reduce friction during the penetration of the projectile into the prey, while remaining solid enough to withstand the forces of impact when meeting a target. A minimum of two techno-functional components can be segregated on the armature of a composite projectile. First, the proximal portion must be shaped to allow the hafting of the implement, and to withstand and transfer the forces of impact from the armature to the shaft of the projectile. When implements are made in advance, the standardization of their proximal portion eases the replacement of damaged armatures as long as the shaft remained intact during the use of the projectile. Second, the distal portion must be given a form fit to pierce the skin of the prey and to induce a lethal wound to the animal. Technological data on the manufacture of osseous projectile points are useful to estimate the point of demarcation between these two techno-functional components on Aurignacian armatures. Indeed, traces of the final stages of their manufacture tend to overlap at the point of maximum width, the final shaping of the distal portion being subsequent to that of the proximal one (Doyon, 2017b; Knecht, 1997; Liolios, 1999). This observation indicates the proximal and distal portions of the implements were shaped separately, and therefore, it suggests the makers of Aurignacian projectile points conceived their osseous hunting implements as objects combining two functionally distinct, yet complementary, components, each subjected to their own shaping imperatives. The point of maximum width likely corresponds to the point of demarcation between these two techno-functional units. This assumption can be tested by borrowing a central concept from evolutionary biology and geometric morphometrics, i.e., shape modularity (Klingenberg, 2008, 2009; Klingenberg and Marugán-Lobón, 2013).

Shape modularity is founded on the ‘theory of *nearly decomposable* systems, in which the interaction amongst the subsystems are weak, but not negligible’ (Simon, 1962, p. 474). In biology, modularity refers to cases where the landmark configuration of an organism can be split into subsets of landmarks, or modules, and where patterns of variation are unevenly distributed between subsets; covariation is greater for landmarks belonging to a given module while being weaker for landmarks across modules (Klingenberg, 2008, 2009; Klingenberg and Marugán-Lobón, 2013). These modules are usually interpreted as a consequence of developmental, functional, or evolutionary processes. Likewise, from a technological perspective, the components of a modular structure should be functionally distinct and their variability is expected to be relatively independent from one another. Shape modularity has seldom been solicited in archaeological studies of material culture. Following Cardillo's (2010) suggestion that lithic points could be divided into a set of modules based on morphological or technological criteria, González-José and Charlin (2012) used shape modularity to assess functional variability of lithic points from Late Holocene contexts in southern Patagonia, while de Azevedo et al. (2014) highlighted differences in the patterns of maintenance of these same points according to their function. In the present paper, the first application of shape modularity in osseous technologies is presented for two types of Aurignacian projectile points, i.e., the split- and massive-based points. The aim is to identify the shapes that were considered fit for hunting and reproduced by the makers of these technologies. Such investigation requires the identification of the techno-functional unit that is more likely to have retained the original shape reproduced during the manufacture of an armature in spite of the various episodes of use, damage, reshaping and recycling it underwent prior to being lost or discarded at a site.

Experimental data on the use and efficiency of osseous projectile technologies tends to demonstrate that the distal portion of an osseous armature is more prone to damages resulting from its utilization than the proximal portion of the object (Bradfield, 2013; Bradfield and Brand, 2013; Doyon and Katz Knecht, 2014; Knecht, 1991, 1997; Newcomer, 1974; Pétillon, 2006). This differential breakage pattern is best explained by the mechanical properties of the raw material itself (Christensen, 2004; Doyon and Katz Knecht, 2014; Knecht, 1991, 1997; Newcomer, 1974) and has implications on how to study the shape of these tools. Assuming that most Aurignacian projectile points discarded at sites had reached their optimal threshold in terms of perceived utility and efficiency (Doyon, 2017b, p. 233), the original rules of production guiding the shaping of the implements' distal portion are likely to have disappeared from the archaeological record. Some archaeological specimens, however, also attest to the repair of the damaged proximal portion and the recycling of fragmented points (Tejero, 2014). The effects of the maintenance of split-based points, for example, are mainly visible on their cross-section morphology, i.e., the original elliptical section becomes more biconvex, while their maximum width and thickness remain more or less the same as these variables were likely determined by the size of the – presumably wooden – shaft to which they were attached. Furthermore, the maintenance of a point's proximal portion may cause its edges to become slightly asymmetrical, albeit not sufficiently deformed to make the original outline unrecognizable (Tejero, 2016). Therefore, the search for original shapes should focus on the hafted proximal end of the point, as this portion is less likely to have undergone substantial modifications over time (see Ahler and Geib, 2000; Smith and DeWitt, 2017; Thomas et al., 2017 for similar arguments in the case of Paleoindian fluted points from North America).

Apart from the extent of reworking it underwent, the proximal shape of Aurignacian projectile points could vary due to the type of raw material used for their manufacture, the alteration incurred following their post-deposition, the intended function of the tool, or a number of learning and population-regulated processes, e.g., socially shared rules of production, skill, copying errors, and cultural drift. Associated evidence from the archaeological record can guide the interpretation of patterned variations as a result of either of these processes; each factor is reviewed below. The mineral and organic composition as well as the structure of the osseous material vary between antler, bone, and ivory (see Christensen, 2004; Knecht, 1991 for a review). This variation could impose some limitations on the sequence of techniques that is applied during the manufacture of a particular tool type. Differences in manufacturing behavior could also be, in some cases, a proximal factor that underlies differences in shape of a given tool type (e.g., Schillinger et al., 2017). Therefore, one should seek for correlations between raw material and the tool type, its shape, or both to assess its effect on morphometric variability. Post-depositional alterations could either result in the damage or the deformation, i.e., compression or bending, of the outline of a bone tool given the anisotropic properties of this raw material. Ideally, these alterations should be identified and the specimens, or the landmarks, affected by this process should be removed from an analysis that aims to document the patterned variation of newly made tools. If function is a primary driver for differences in weapon form, one should expect to find discrete associations between the shape of the tool and either the type of prey that was hunted, the ecological niches in which the points were recovered, or some evidence of its use in different tasks such as penetrating, slicing, or cutting. However, with regard to this last factor, and unlike their lithic counterparts, the edges of osseous points do not have lacerating properties. The smooth surfaces of Aurignacian implements suggest their intended function was primarily to pierce the skin and penetrate sufficiently deep into the prey to perforate the internal organs and cause a lethal hemorrhage (Knecht, 1991, 1997). Therefore, in the present study, functional associations will only be sought between the artefact shape and the type of prey as well as the ecological niches in which the armatures were used.

Included amongst the learning and population regulated processes are socially shared rules of production (Lycett and von Cramon-Taubadel, 2015; Schillinger et al., 2014), skill (Eerkens, 2000; Ingold, 2002; Minar, 2001), copying errors (Eerkens and Lipo, 2005; Gandon et al., 2014; Hamilton and Buchanan, 2009; Schillinger et al., 2014), and cultural drift (Binford, 1963; Koerper and Stickel, 1980). Socially shared rules of production can be identified through the occurrence of a weapon form at multiple sites of comparable age. The geographic distribution of these forms would signal the territory inhabited by the populations amongst which these rules were shared. Differences in skill are more likely to result in the variation of a given shape rather than in the long-lasting production of an altogether new weapon form. Copying errors, on the contrary, are cumulative by nature. If this process is in action, one should expect to identify gradual trends in time from an original to a new tool shape. Likewise, if cultural drift is responsible for the patterned variations, gradual trends should be observed in both space and time. Lastly, morphological differences could potentially be the result of temporal drift (e.g., Rigaud et al., 2015, 2018). In this scenario, stratified sites should testify to the appearance and disappearance of specific artefact forms through time. However, chronology, in and of itself, does not provide an explanation as to how and why morphological variability was introduced in the production sequence. Therefore, temporal drift must be explained by other processes such as copying errors, cultural drift or changes in the favored rules of production.

Materials and Methods

The sample considered in the present study comes from 38 sites and comprises 499 projectile points (294 split- and 205 massive-based points; Tab. 1). The technological, morphometric, and use-wear data were collected on the archaeological specimens in the course of two doctoral projects (Doyon, 2017b; Knecht, 1991). The first data collection was carried out by Heidi Katz Knecht in 1987–1988 and focused on assemblages from Western Europe. The second was conducted by myself in 2015 and aimed to complement Katz Knecht's observations to obtain a continental perspective of the phenomena. Therefore, assemblages from Southern and Central Europe were targeted. Heidi Katz Knecht provided access to the data she collected by sharing recording sheets and photographs of the archaeological specimens. This information was digitized in high resolution and is now curated on the server of the Hominin Dispersal Research Group at the Department of Anthropology of the University of Montreal. Both data collections followed the same methodology to ensure the gathered information would be comparable. Complete points and fragments were studied during this phase of the projects. In an effort to maximize the sample size considered in the present study, all specimens retaining their point of maximum width were selected.

A 36-segment polar grid was superimposed on photographs of the plan view of the superior aspect of the artefacts, i.e., the aspect where the antler spongiosa, or traces of it, is not present, in order to record the landmarks that summarize their shape configuration. The origin of this grid was aligned at the intersection between the main axes of the tool, i.e., the maximum length and width (Fig. 1a). Following the superimposition of the grid, the digitization of the shape configuration consists of recording 36 landmarks for each specimen. The use of photographs to record landmarks implies the shape of the objects is modeled in only two dimensions. The comparison of 3-dimensional shapes from 2-dimensional landmark configurations can indeed result in the loss of information on the overall morphometric variability. However, this loss is not statistically significant for almost flat objects (Velhagen and Roth, 1997), which is the case for Aurignacian osseous projectile points. Therefore, the primary assessment of the morphometric variability of these implements focused on the outline of the tool. The armature's thickness was later considered in the clustering method as a means to identify the proximal shapes reproduced in the manufacture of projectile points (see below). Landmarks were recorded at the intersection of a grid segment and an intact portion of the point's outline in order to *de facto* rule out variability that could be attributed to post-depositional processes. The first landmark corresponds to the right end point of the maximum width and the 35 remaining landmarks are consecutively recorded clockwise from one grid segment to the next. The same procedure was carried out for the damaged points with the exception that missing landmarks were given [NA,NA] coordinates in the *.nts file where the shape configurations were saved (Fig. 1b). The data was subsequently uploaded in R-CRAN (R Development Core Team, 2008) using the '*geomorph*' package for morphometric analysis (Adams et al., 2016; Adams and Otárola-Castillo, 2013). No attempt to interpolate missing landmarks was undertaken in the present study. However, the sample size varies from one analysis to the next. For each analysis, the specimens included are those with known coordinates for each landmark considered (see below).

Shape can be broken down into two constitutive elements: the geometry of an object, synthesized or modeled from the landmarks' configuration of the outline, and its size. To compare distinct shape configurations, they must be aligned using the Generalized Procrustes Analysis (GPA) (Fig. 1c). This analysis consists of three procedures. First, it translates the configurations to center them on a common centroid. Second, it iteratively rotates the landmark constellations to ensure their adequate alignment. Finally, the shape configurations are iteratively scaled to the same centroid size in order to minimize the standard error between the various configurations and the mean shape, i.e., a hypothetical shape for which each landmark coordinate equals the average locus of the corresponding landmarks in a given sample. This scaling nullifies the effect of size when comparing shapes and allows the analysis to be performed solely on the object's geometry (Rohlf and Slice, 1990; Slice, 2005; Zelditch et al., 2004). To ensure comparability, a GPA must be performed every time a subsample is selected, e.g., when the analysis is conducted solely on split- or massive-based points as opposed to both types simultaneously. This step is required to quantify how a given shape varies relative to the others included in the subsample. From the GPA, two variables can be extracted. The first corresponds to the mean shape configuration and the second is the specimens' centroid size, i.e., the sum of squared distances of a series of major landmarks to their common centroid (Bookstein, 1991).

Testing for shape modularity implies calculating a covariance ratio *CR* of a hypothetical modular configuration and comparing it to a number of randomly generated ones. Non-parametric testing allows for the quantification of *CR* and its associated *p-value*. The null hypothesis of an equal variation in the covariation matrix is rejected at $\alpha = 0.05$ when *CR* is lower than 1 (Adams, 2016). The rejection of the null hypothesis entails the techno-functional components of a point should be studied separately in order to assess their respective contribution to the overall morphometric variability. For this test, only complete specimens with data for the 36 landmarks are selected ($n = 111$; split-based points: $n = 64$; massive-based points: $n = 47$).

After defining the limits of each techno-functional component (Fig. 2d), a principal component analysis (PCA) allows for the general assessment of their morphometric variability by projecting the specimens on Kendall's tangential shape space (Slice, 2001). PCAs are produced for each techno-functional component separately. All the landmark coordinates of a given techno-functional component, i.e., the proximal or distal portion of a point, had to be known for a specimen to be included in the corresponding PCA. Consequently, the sample size for the PCA of the proximal portion of the points ($n = 285$; split-based points: $n = 139$; massive-based points: $n = 146$) differs from that of the distal portion ($n = 111$; split-based points: $n = 64$; massive-based points: $n = 47$). PCA plots are produced and the relative warps for each principal component are extracted and illustrated.

Finally, a focus on the proximal portion of the points aimed to identify clusters of armatures similar both in shape and in size. To this end, the values for the first two principal components of the morphometric variability and the centroid size of the specimens were extracted from the corresponding PCA and combined as dependent variables in a new PCA, along with the point's thickness perpendicular to the maximum width. The proximal length and maximum width, the geographic coordinates, the name of the sites, and the name of the region to which these localities belong were added in the

PCA as quantitative and qualitative independent variables. The independent variables had no weight on the PCA; they were only included to quantitatively and qualitatively characterize the shape clusters (see below). A hierarchical clustering technique complemented with a *k-mean* aggregation procedure was performed with the results of this second PCA in R-CRAN (R Development Core Team, 2008) using the '*FactoMineR*' package (Lê et al., 2008). A non-parametric test to compare the relative proportions was computed to characterize the shape clusters and to find sites or regions where they are over- or underrepresented. This test follows the hypergeometric distribution $H(n_c, n_m/n, n)$, where n is the total sample size, n_m is the sample size for a given site or region and n_c is the sample size for a given cluster (Husson et al., 2011). The data and R code used in the present research is available upon request.

Results

In the sample considered for the present study, more than one fifth of the points are complete (split-based points: 21.8%; massive-based points: 22.0%; Tab. 1). Proximal and distal damages are respectively present on 18.3% and 27.0% of split-, and 1.9% and 47.5% of massive-based points (Tab. 2). Both proximal and distal damage was recorded on 47.0% of split- and 41.9% of massive-based points. The remaining portion of the sample shows lateral damage, sometimes in combination with proximal and/or distal damage (split-based points: 7.8%; massive-based points: 8.8%). Aside from three specimens, i.e., two made of bone and one made of ivory, all split-based points are made of antler. Massive-based points were predominantly produced from antler (73.1%) but also from bone (21.5%) and ivory (5.4%). In Western Europe, all massive-based points were made of antler with the exception of one specimen made of bone from La Ferrassie. In Central Europe, the three raw materials were used for the manufacture of this tool type. However, points made of bone predominantly come from Potočka zijavka and those in ivory are mostly found at Mamutowa.

The modularity test (Fig. 2) produces significant results for both split- (observed $CR = 0.885$; $p = 0.001$) and massive-based points (observed $CR = 0.92$; $p = 0.038$). These results indicate the patterns of covariation are unevenly distributed between the proximal and the distal portions of complete specimens, which provide quantitative support to technological and experimental observations. As suggested by the overlap of the traces of manufacture, the maximum width is identified as the point of demarcation between these two techno-functional components (Fig. 1d). The maximum width itself belongs to the distal component of the armature. The uneven distribution of the patterns of covariation between both techno-functional units implies different processes were likely responsible for their respective variability. In order to avoid conflating these factors in the following analysis, shape variation for each techno-functional unit is addressed separately.

The first two principal components explain 95.16% of the total variation of the points' proximal portion (Fig. 3a). They relate to the maximum width relative to the proximal length (PC1: 85.92%) and the relation between the morphology of the base and the degree of lateral convergence (PC2: 9.24%). The lateral asymmetry of the proximal portion of the points only accounts for 1.93% of the total variation as reflected on the third principal component. Both projectile point types significantly differ from one another along the first two principal components. When the raw material is taken into account (Fig. 3b), no statistically significant differences were observed for the principal components values of massive-based points' proximal portion. The values obtained for armatures in bone or in ivory are comprised within the range of variation observed for those made of antler.

For the distal portion of the points, the first two principal components explain 95.23% of the total variation (Fig. 4a). The first principal component synthesizes the maximum width relative to the distal length combined with the morphology of the tip (PC1: 91.22%), while the second relates to the lateral asymmetry of the distal portion (PC2: 4.01%). Both types are considerably overlapping, although split-base points tend to have a smaller distal length relative to their maximum width compared to massive-based points. Specimens made of bone or ivory display principal components' values within the range of variation observed for antler armatures (Fig. 4b).

The hierarchical clustering procedure identifies eight shape clusters (S01 to S08) for split-based points (Fig. 5–6). Specimens assigned to distinct clusters differ both in terms of their size and their shape. Seven shape clusters (M01 to M07) are identified for massive-based points when applying the same method (Fig. 7–8). However, with the exception of the specimen assigned to the cluster M04, the implements belonging to the six other shape clusters show substantial morphological overlap (Fig. 7b), and only differ from one another when the size of the armatures is considered (Fig. 7c).

The geographic distribution of the shape clusters at a continental scale shows contrasting patterns when both projectile point types are compared (Tab. 4–5). The proximal shapes identified for split-based points are found over vast regions of Europe. However, five of these shapes are relatively more abundant in some regions (Tab. 4). This is the case for S01 in Cantabria and in the Western Pyrenees region, for S02 in the Carpathian Mountains region, for S05 in the Meuse watershed and the Swabian Jura, for S06 in the Eastern Pyrenees region, and for S07 in Southwest France. This regionalization pattern is also observed in the absence of specimens assigned to the proximal shape S05 in Southwest France. At a continental scale, S04 is absent from the Meuse watershed, the Swabian Jura, and the Western Carpathian while being present in all the other regions to the South.

In contrast, the proximal shapes identified for massive-based points are predominately aggregated locally or regionally. Some forms are indeed found at a single site such as M06 in Willendorf and M07 in Mamutowa, or at a number of sites from the same region such as M03 in Blanchard, La Ferrassie and Les Vachons, or M04 in Vindija and Mladeč. As a general rule, when a proximal shape of a massive-based point is overrepresented in Western Europe, it is usually underrepresented in Central Europe, and vice versa (Tab. 5).

Discussion and Conclusion

The present study represents a first attempt to apply landmark-based geometric morphometrics and use the concept of shape modularity to analyze the morphometric variability of osseous projectile technology. The results obtained from the shape modularity test supports the idea that Aurignacian populations conceived their osseous armatures as tools combining two distinct, yet complementary, components fulfilling different functions. The shaping of either component clearly followed specific guiding principles. While similarities are observed for the shape of the artefacts' distal portion, both types differ significantly with regard to the morphology of their hafted portion. The application of geometric morphometrics to explore the variability of the hafted portion allows the identification of the proximal length relative to the maximum width as the principal component of their shape variation. This result has important implications for our understanding of Aurignacian osseous projectile technology. If the points' maximum width and thickness were constrained by the cross-section's dimensions of the wooden shaft on which they were attached (Tejero, 2014, 2016), the points' proximal length, and their proximal morphology, likely varied based on the conception prehistoric artisans had of a suitable hafting mechanism. Reworking of damaged proximal portions seems only to have marginally affected the morphology of the points as attested by the low percentage of variation resulting from lateral asymmetry.

When both the objects' size and geometry are taken into consideration, eight shape clusters for split- and seven for massive-based points can be described. Since the split-based point clusters differ both in terms of size and shape, we can infer that their makers tried to reproduce one of eight distinct proximal shapes when manufacturing an armature. On the contrary, with the exception of M04, the clusters identified for massive-based points are similar in shape but distinct in size. This result suggests the makers of this tool type likely aimed to reproduce one of two proximal shapes, one of which could take a number of variants. It should be stressed that the number of proximal shapes identified per tool type in this study must be considered a minimum value, which may increase in future studies conducted on an enlarged sample. The development of a method to accurately estimate the coordinates of missing landmarks could also result in an increased number of proximal shapes.

The geographic distribution of split- and massive-based points' proximal shapes highlights conspicuous differences that are best understood when two technological aspects are considered, i.e., raw material selection and the complexity of the reduction sequences for the manufacture of these implement types. The split-based points found in the archaeological record were almost exclusively made of antler. Given its higher percentage of organic matrix compared to bone or ivory, its microstructural organization, and its ensuing mechanical properties (Albrecht, 1977; Christensen, 2004; Currey, 1979, 1984, 1999, 2002; Knecht, 1991), antler is more suitable for the manufacture of the proximal split than the two other raw materials. This step of the reduction sequence constitutes a critical moment (*sensu* Lemonnier, 1976) in the manufacture of this tool type, and it requires a certain level of mastery. Indeed, failure to produce a proximal split would result in the loss of a suitable blank, or of a substantial portion of it, for the manufacture of a point. Use-wear studies combined with experimental replications suggest the production of a proximal split could be achieved through the application of a number of processes such as cleaving the blank (Knecht, 1989, 1991, 1993) or the flexion of the blank subsequent to its incision (Nuzhnyi, 1998; Tartar and White, 2013). The selection of a unique raw material to be transformed following a given sequence of techniques in order to achieve particular morphologies that show patterns of regionalization over vast territories suggests that somewhat strict rules of production guided the Aurignacian makers of split-based points. On the contrary, massive-based points could be made of antler, bone, or ivory, and the shaping of their hafted proximal portion can be achieved simply by scraping. Furthermore, the geographic distribution of the proximal shapes identified in the present study is mainly characterized by their regional or local aggregation. Together, these observations indicate an increased flexibility in the rules of production of this tool type compared to those of the split-based points.

If utilization and resharpening of the points account for the morphometric variability of their distal portion (Doyon and Katz Knecht, 2014; Liolios, 1999; Tejero, 2014; Turk, 2002, 2003, 2005), other factors responsible for the patterned variations observed on the proximal portion of Aurignacian osseous armatures must be considered. Raw material availability could explain the predominance of bone points at Potočka zijavka and of ivory points at Mamutowa. Indeed, the numerous cave bear remains at Potočka zijavka indicate this locality served as hibernating den for this animal. It remains, however, difficult to assess if Aurignacian groups visited this site to kill hibernating prey at a time when they were most vulnerable (e.g., Withalm, 2004), or if they exploited carcasses of animals that died of natural causes. In the case of Mamutowa, this site is located in a region where mammoth hunting and exploitation by Aurignacian populations are documented (Vercoutère and Patou-Mathis, 2010). Nonetheless, Potočka zijavka yielded specimens with proximal shapes highly similar to those produced in antler found at La Ferrassie. On the other hand, although M07 was exclusively found at Mamutowa, this shape corresponds to a variant of one of the main proximal shapes identified for massive-based points. As mentioned above, these variants mainly differ when the implement's size is considered. Consequently, in addition to having an effect on the type of projectile point to be manufactured, it appears the raw material mainly determined the size of massive-based points but had little bearing on their proximal morphology.

It has been suggested that differences in function could explain differences in weapon forms (Tartar and White, 2013). This hypothesis usually conflates a number of elements, i.e., function could relate to the type of projectile onto which the armatures were hafted, the type of prey targeted by the hunters, or the ecological niche in which the projectiles were used. It is generally accepted that Aurignacian osseous projectile points were hafted on spears to be launched with spear-throwers, although some researchers suggested the smallest split-based points could have been hafted on arrows (Odar, 2011; Otte, 2014). Given that the other components of Aurignacian projectile technology such as the presumably wooden shaft and/or foreshaft are absent from the archaeological record, questions relating to the type of the projectile on which these armatures were affixed and their mode of propulsion remain open. Future ballistic experiments combined with morphometric analysis could potentially provide informative clues as to the type and extent of damages resulting from the use of different hunting technologies. Regardless of the type of projectile, zooarchaeological evidence indicates the makers of the Aurignacian material culture were efficient hunters able to adapt their subsistence behaviors to a variety of biotas. Horses were one of the favored prey, but they also exploited other animals available in the many ecological niches of the European continent at the time (Vercoutère and Patou-Mathis, 2010 for a comprehensive review). The geographic distribution of the proximal shapes of Aurignacian osseous projectile points seems not to be limited to a particular niche. It therefore seems unsubstantiated, given the information available at this time, to explain the morphometric variability of a particular tool type solely with functional imperatives surrounding the use of this technology.

The effects of learning and population regulated processes on the morphometric variability of split- and massive-based points are somewhat difficult to assess at this point. The three principal components of variation identified for the proximal portion of the implements in the present study leave unexplained only a small percentage of the overall variability. Differences in skill could probably be a factor that caused this variation. The biggest challenge, however, relates to our abilities to assess the impact of population-regulated processes and temporal drift on the morphometric variability of either tool types. Establishing a precise chronology for the presence of each proximal shape is difficult since the Aurignacian technocomplex occurred at a time that is near the limit of applicability of ^{14}C dating methods. Yet, Aurignacian osseous projectile points were often found at localities that were visited for relatively short periods of time. This is especially true for the sites in Southern and Central Europe, i.e., Provence-Liguria, South-central Europe, and Western Carpathians, where archaeological evidence suggests they mainly served as hunting camps (Doyon, 2017a, under review), or were recurrently occupied on a seasonal basis (Adams, 2009). Nevertheless, evidence from stratified sites in southwestern France that attest to lengthier occupations, e.g., abris Castanet and Blanchard, La Ferrasie, and Isturitz, suggests the contemporaneous occurrence of multiple proximal shapes in their archaeological horizons, which could be an argument in favor of the co-occurrence of micro-traditions within the Aurignacian (see Riede and Pedersen, 2018 for a similar phenomenon within the Hamburgian culture). However, more contextual and chronometric data are required to state with confidence if this pattern indeed represents contemporaneity or if it is merely the result of a palimpsest of occupations.

Despite the limitations imposed by the archaeological record, which prevent us from precisely distinguishing the relative effects of the aforementioned processes on the morphometric variability of Aurignacian osseous projectile points, the ethnographic literature highlights the fact that the adoption of a particular hunting technology results from a number of complex decisions, and that the knowledge surrounding the manufacture and use of these technologies is socially shared (Churchill, 1993; Ellis, 1997). This knowledge includes the type of projectile that should be manufactured, the ways in which they should be used, but most importantly the technological sequence leading to their production. It should be stressed that variations in the proximal shape of Aurignacian armatures perhaps originated from minute differences in the manufacturing processes of the points, i.e., differences in how an armature should be made in order to be considered fit for hafting and hunting prey, rather than from the imposition of a mental template on the osseous material (*sensu* Schillinger et al., 2017). In this sense, the proximal portion of split- and massive-based points seems to have preserved clues allowing us to identify the socially shared rules of production that guided their manufacture, and therefore, highlights micro-traditions within the Aurignacian technocomplex similar to those recognized form Middle Stone Age contexts in Africa (Archer et al., 2016) and from Hamburgian contexts in northern Europe (Riede and Pedersen, 2018). The differences in the geographic distribution of the proximal shapes of split- and massive-based points are surely informative of population dynamics such as coalescence and fragmentation, similar to those documented from southern Africa throughout the MIS5 to the MIS2 (Mackay et al., 2014). If this is the case, the variability in the proximal shape of massive-based points combined with their respective geographic distribution likely signal convergent solutions to a same problem, i.e., producing a projectile point with a proximal portion that can be easily be shaped without risking to damage the blank in the process. On the other hand, the pattern described for split-based points probably implies more generalized inter-regional group interactions either through the movement of individuals over long-distance or the transfer of complex knowledge across long-distance through short chains of interaction (e.g., Lombard and Högberg, 2018).

The results and discussion presented here set forth a previously unexplored research perspective for studies on the European Early Upper Palaeolithic. Research conducted thus far on the identification of the social groups within the Aurignacian metapopulation and the extent of their interactions relied on multiple sources of evidence such as the distribution of ornament types (Vanhaeren and d'Errico, 2006) and the technological organization of their manufacture (Heckel, 2018), the geographic distribution of manufacturing techniques for lithic (Bon, 2002; Michel, 2010; Teyssandier, 2007) and bone technologies (Albrecht et al., 1972; Goutas and Tejero, 2016; Knecht, 1991; Liolios, 1999; Tartar and White, 2013), bladelet morpho-technology (Le Brun-Ricalens and Bordes, 2007; Riel-Salvatore and Negrino, 2018), as well as lithic raw material procurement strategies (Caux, 2015, 2017; Féblot-Augustins, 1997, 1999, 2009; Grimaldi et al., 2014; Porraz et al., 2010; Riel-Salvatore and Negrino, 2009). By applying geometric morphometrics and the concept of shape modularity to the analysis of

Aurignacian osseous projectile points, it is now possible to add the morphometric variability of their proximal portion to this list of evidence that can serve to identify prehistoric group membership. Future research conducted with the aim of finding correlations between these different proxies will undoubtedly be successful in shedding light on the extent of interactions of past populations at a turning point of the European Palaeolithic.

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Legends of figures and tables

Figure 1: a: Polar grid superimposed on a split-based point from Cova de L'Arbreda (the green line linking landmarks 1 and 19 corresponds to the maximum width; the blue line linking landmarks 10 and 28 corresponds to the maximum length; the green crosses indicate where the landmarks were recorded; Scale = 1 cm); b: Corresponding landmarks coordinates saved in the *.nts file; c: Generalized Procrustes Analysis (GPA) of the complete split-based points included in the present study; d: Demarcation between the distal and proximal modules and their corresponding landmarks.

Figure 2: a: Results of the modularity test for split-based points (observed $CR = 0.885$; $p = 0.001$); b: Results of the modularity test for massive-based points (observed $CR = 0.92$; $p = 0.038$). The black arrows indicate the observed *CR* value for each sample considered.

Figure 3: a: Projection of the first two principal components of shape variation for the proximal portion of split- (red) and massive-based (black) points; b: Projection of the first two principal components of shape variation for the proximal portion of massive-based points made of antler (black), bone (red), and ivory (green). *Note*: Only the specimens with all the landmarks of the proximal module are included in these graphs.

Figure 4: a: Projection of the first two principal components of shape variation for the distal portion of split- (red) and massive-based (black) points; b: Projection of the first two principal components of shape variation for the distal portion of armatures made of antler (black), bone (red), and ivory (green). *Note*: Only the specimens with all the landmarks of the distal module are included in these graphs.

Figure 5: a: Projection of the hierarchical clustering tree for split-based points on the factor map; b: Projection of the first two principal components of shape variation for the proximal portion of split-based points by shape cluster; c: Range of variation of the proximal length by shape cluster. *Note*: The horizontal line indicates the average for the sample considered in the present study.

Figure 6: Principal warps for the shape variation of the proximal portion and sample of split-based points assigned to their corresponding shape cluster. Scales = 1 cm.

Note: Grey scaled photographs are part of the Heidi Katz Knecht Collection curated at the Hominin Dispersal Research Group Laboratory at the University of Montréal.

Figure 7: a: Projection of the hierarchical clustering tree for massive-based points on the factor map; b: Projection of the first two principal components of shape variation for the proximal portion of massive-based points by shape cluster. *Note*: The dash-lined box highlights the data for the shape M04; c: Range of variation of the proximal length by shape cluster. *Notes*: 1) The horizontal line indicates the average for the sample considered in the present study; 2) The dash-lined box highlights the data for the shape M04.

Figure 8: Principal warps for the shape variation of the proximal portion and sample of massive-based points assigned to their corresponding shape cluster. Scales = 1 cm. *Note*: Grey scaled photographs are part of the Heidi Katz Knecht Collection curated at the Hominin Dispersal Research Group Laboratory at the University of Montréal.

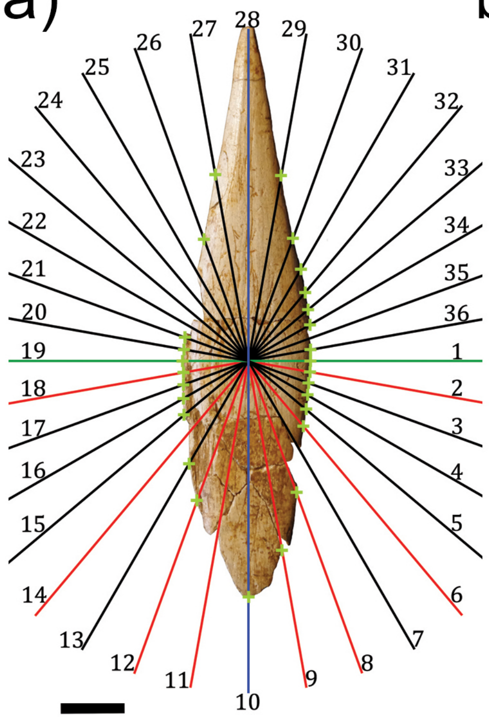
Table 1: Contextual data of the sample of points considered in the present study.

Table 2: Percentage and location of damages recorded on the specimens analyzed in the present study.

Table 3: Over- (black) and underrepresentation (red) of split-based point proximal shape by region and by site.

Table 4: Over- (black) and underrepresentation (red) of massive-based point proximal shape by region and by site.

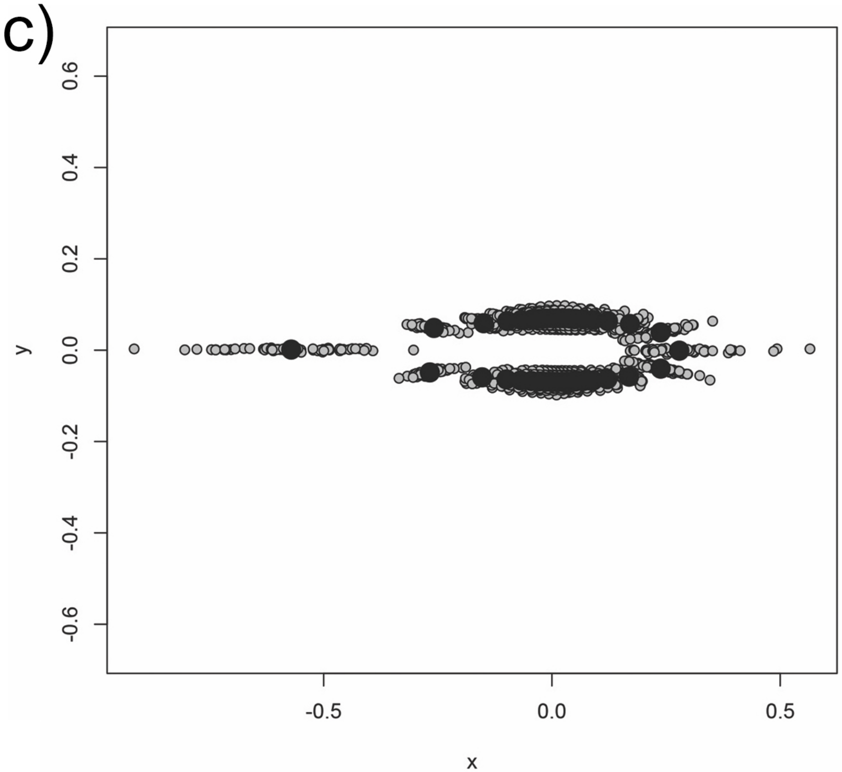
a)

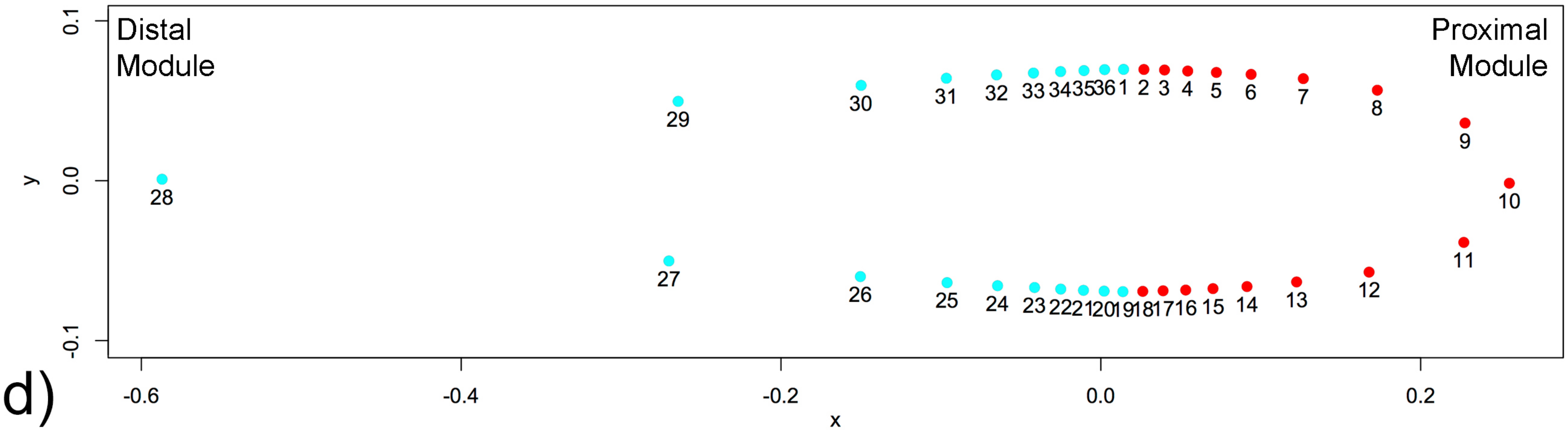


b)

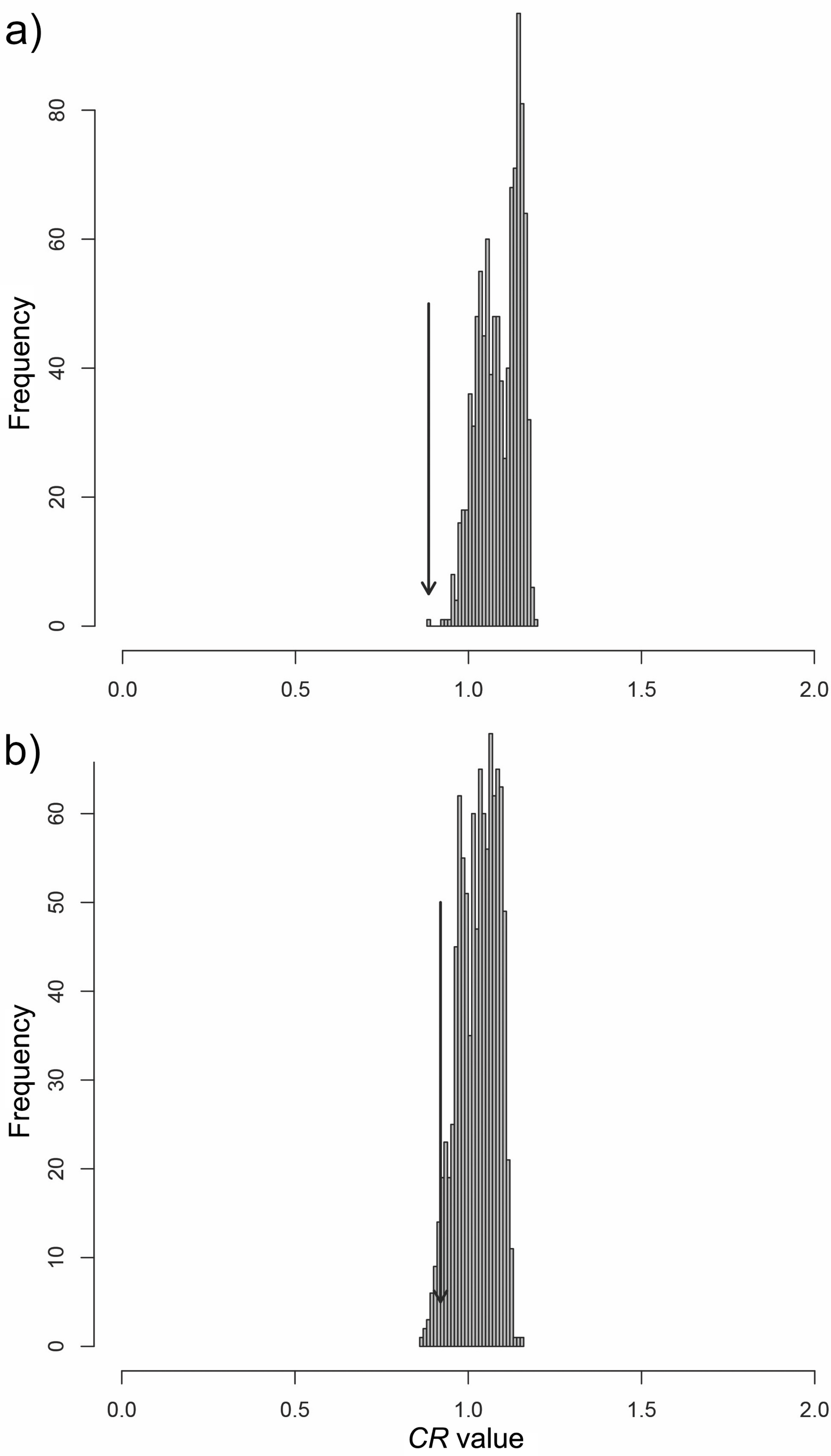
Land_ID	X	Y
1	5.336	5.339
2	5.331	5.165
3	5.318	4.982
4	5.287	4.79
5	5.255	4.572
6	5.215	4.304
7	NA	NA
8	5.117	3.201
9	4.858	2.402
10	4.341	1.716
11	NA	NA
12	3.561	3.183
13	3.44	3.767
14	NA	NA
15	3.365	4.511
16	3.338	4.756
17	3.333	4.965
18	3.333	5.159
19	3.329	5.338
20	3.342	5.516
21	3.356	5.699
22	NA	NA
23	NA	NA
24	NA	NA
25	NA	NA
26	3.65	7.239
27	3.833	8.232
28	NA	NA
29	4.867	8.305
30	5.046	7.278
31	5.171	6.769
32	5.237	6.399
33	5.282	6.118
34	5.175	5.815
35	NA	NA
36	5.331	5.503

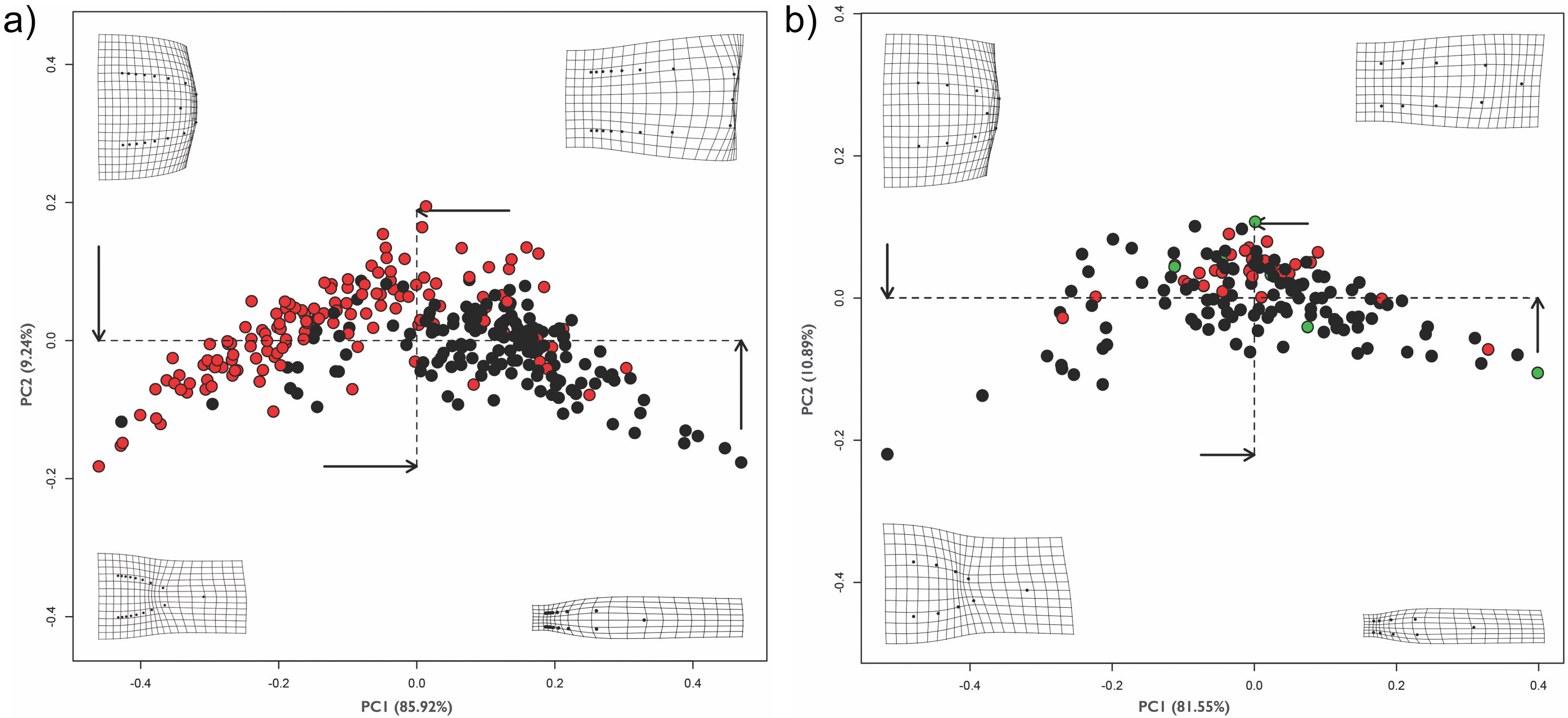
c)



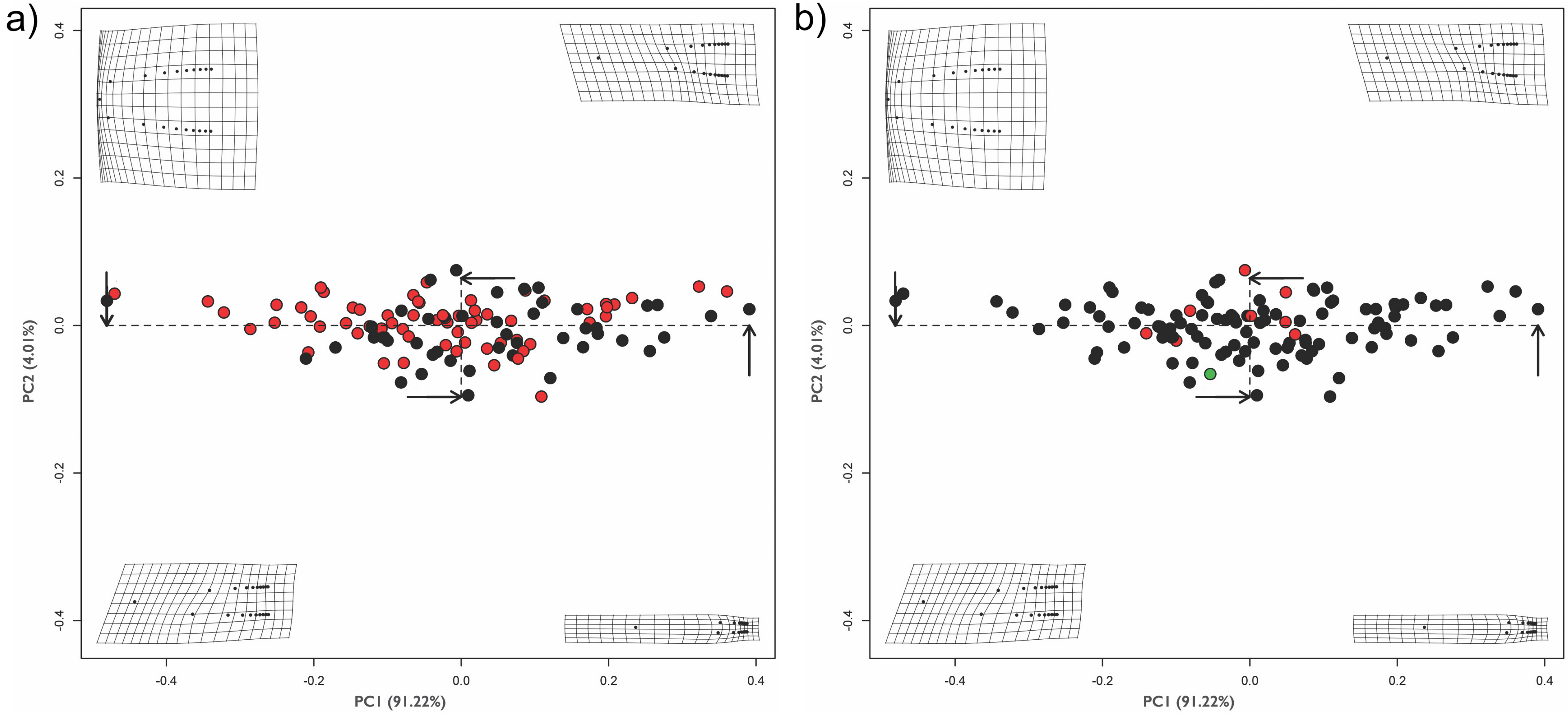


d)

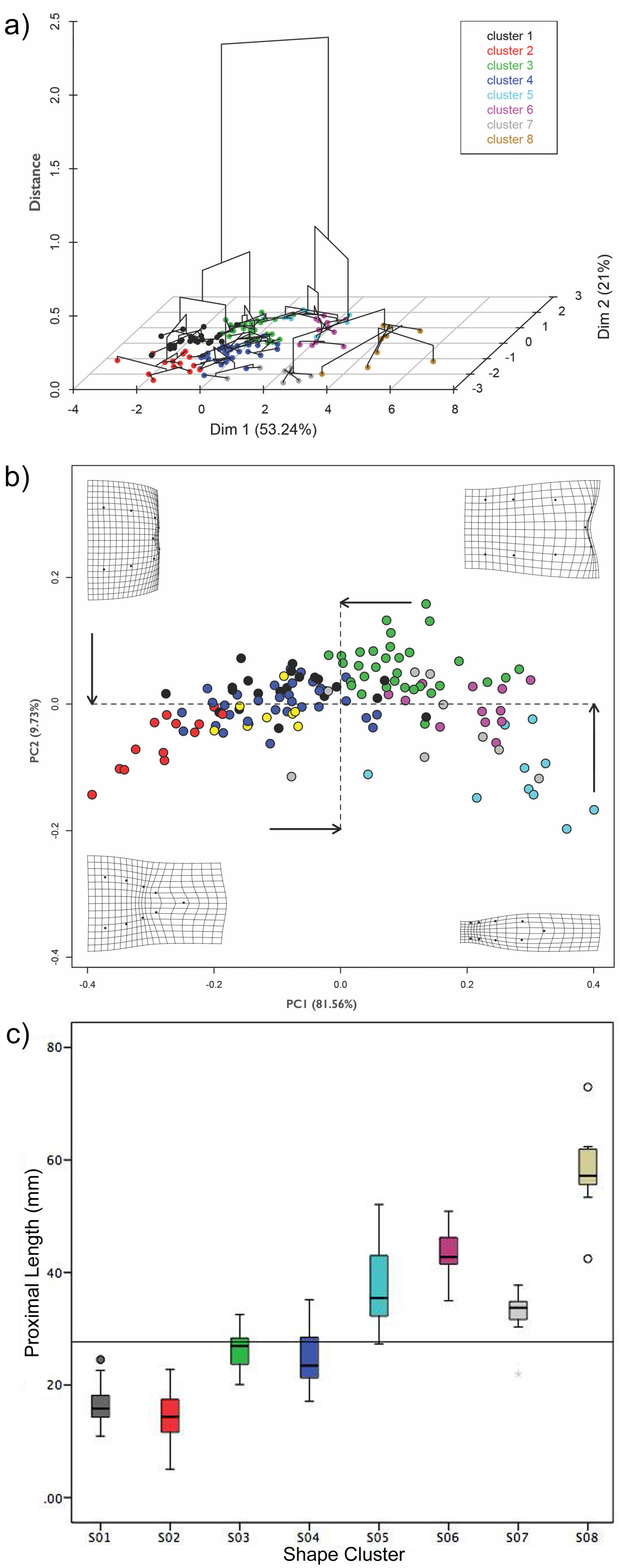

a)
Frequency
0
20
40
60
80
0.0
0.5
1.0
1.5
2.0
b)
Frequency
0
10
20
30
40
50
60
0.0
0.5
1.0
1.5
2.0
CR value

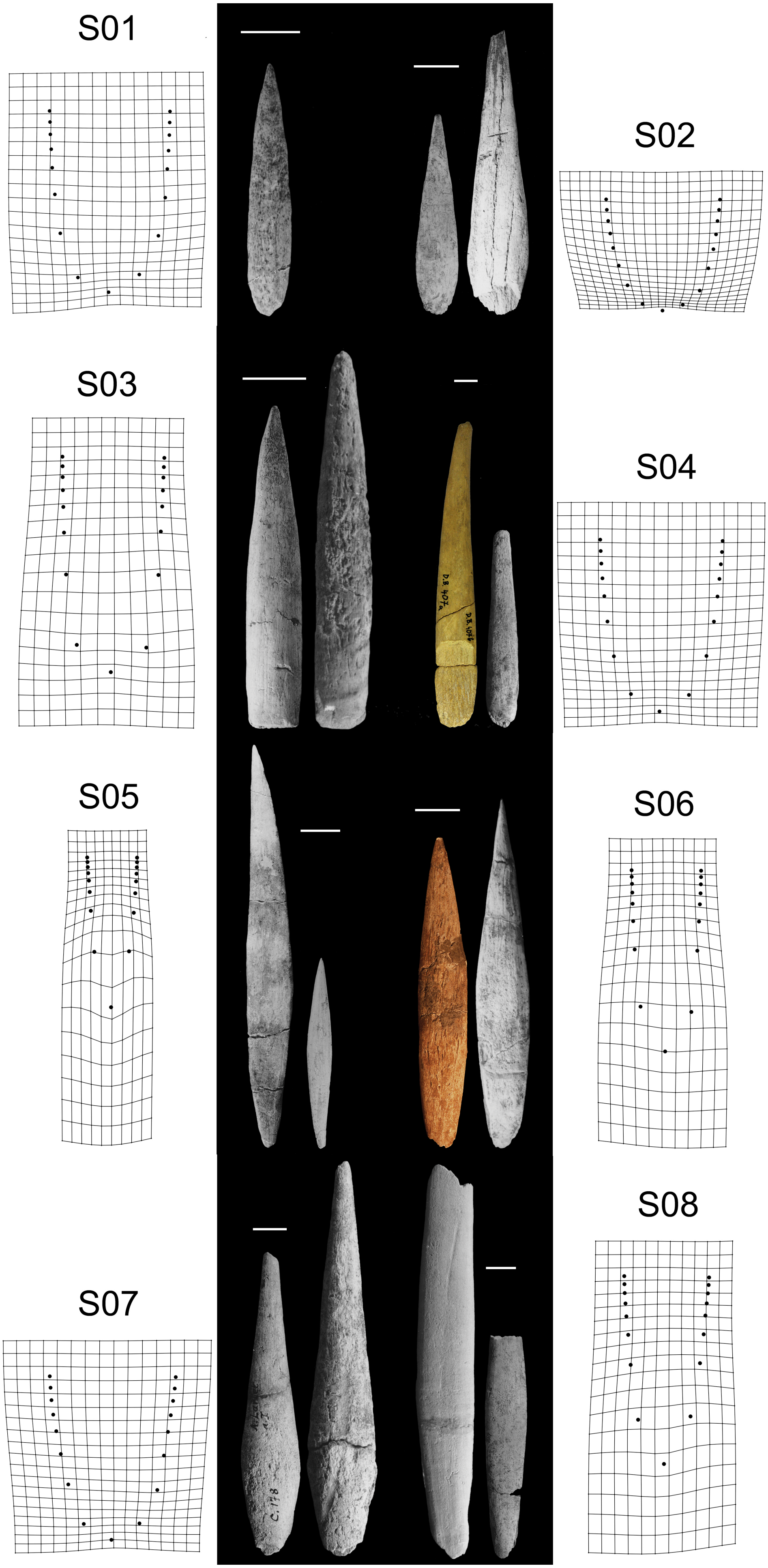


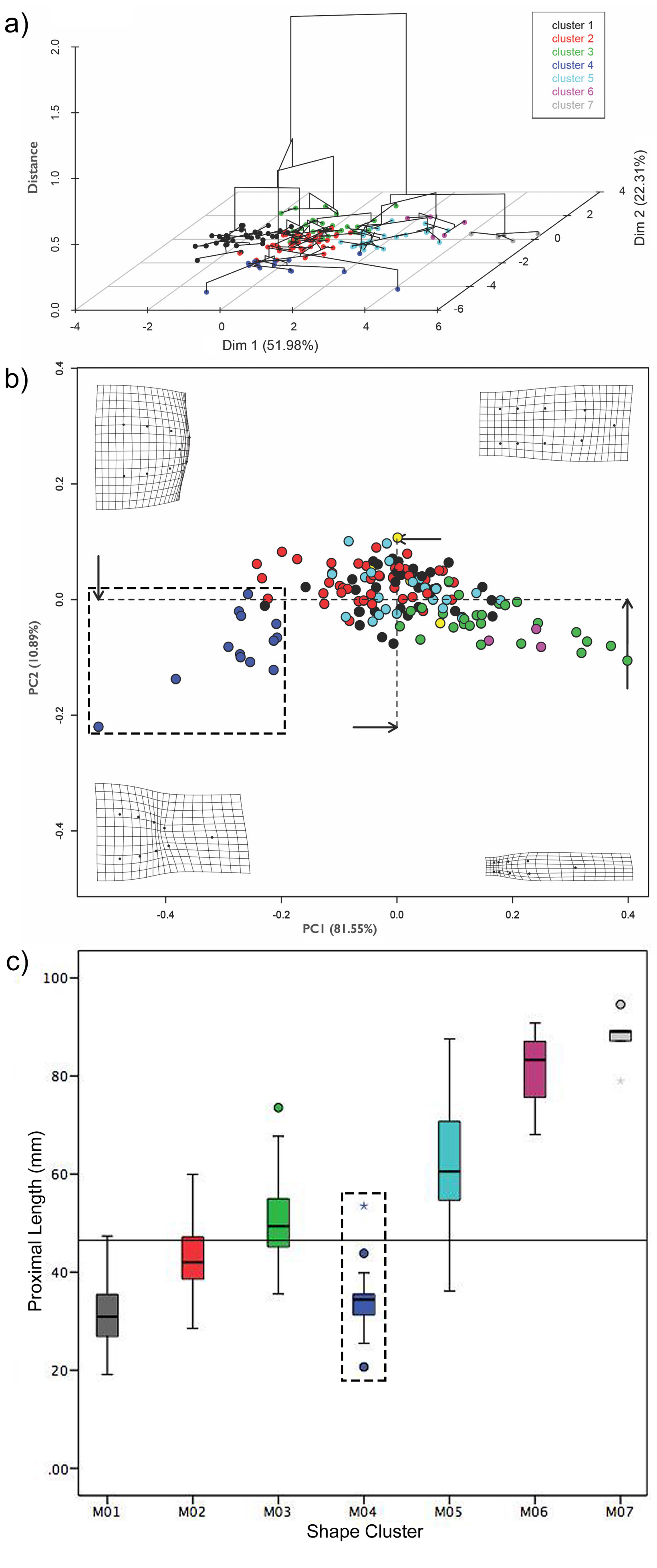
a)
b)
PC1 (85.92%)
PC2 (9.24%)
PC1 (81.55%)
PC2 (10.89%)
0.4
0.2
0.0
-0.2
-0.4



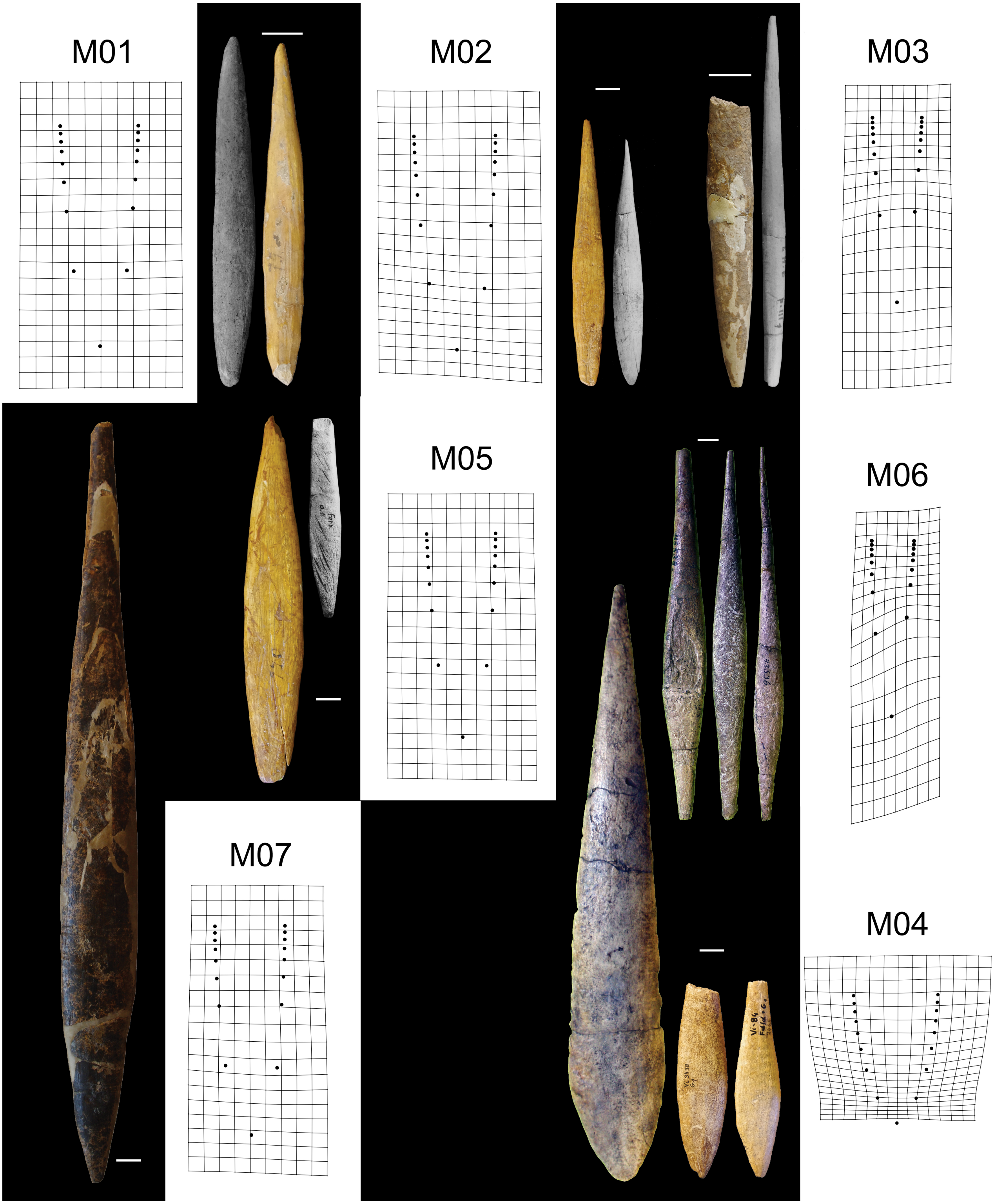
a)
b)
PC2 (4.01%)
PC1 (91.22%)
0.4
0.2
0.0
-0.2
-0.4
-0.4
-0.2
0.0
0.2
0.4


a)
Distance
0.0
0.5
1.0
1.5
2.0
2.5
cluster 1
cluster 2
cluster 3
cluster 4
cluster 5
cluster 6
cluster 7
cluster 8
-4
-2
0
2
4
6
8
Dim 1 (53.24%)
-3
-2
-1
0
1
2
3
Dim 2 (21%)
b)
PC2 (9.73%)
0.2
0.0
-0.2
-0.4
-0.4
-0.2
0.0
0.2
0.4
PC1 (81.56%)
c)
Proximal Length (mm)
80
60
40
20
.00
S01
S02
S03
S04
S05
S06
S07
S08
Shape Cluster


S01
S02
S03
S04
S05
S06
S07
S08



a)
cluster 1
cluster 2
cluster 3
cluster 4
cluster 5
cluster 6
cluster 7
Distance
Dim 1 (51.98%)
Dim 2 (22.31%)
b)
PC2 (10.89%)
PC1 (81.55%)
c)
Proximal Length (mm)
Shape Cluster
M01
M02
M03
M04
M05
M06
M07


M01
M02
M03
M05
M06
M07
M04