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1 **On the shape of things: A geometric morphometrics approach to investigate**
2 **Aurignacian group membership**

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13
14 **Abstract**

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

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

34

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

37

38 **Highlights**

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

47

48 **Introduction**

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

63 Previous attempts have failed to identify patterned variation amongst split- and
64 massive-based points (Albrecht et al., 1972; Clément and Leroy-Prost, 1977; Knecht,
65 1991; Turk, 2002, 2003, 2005). The methodology and the analytical tools selected to
66 study the armatures' shape are two factors at the root of this inconclusive outcome. From
67 a methodological standpoint, the works by Turk (2002, 2003, 2005) focused on the
68 absolute and relative dimensions of massive-based points from Central Europe. This
69 approach allowed him to identify use and resharpening as primary converging processes
70 that produce morphometric variability on the distal portion of the implements, however, it
71 failed to address the shape variability of the proximal portion of these objects. Other
72 researchers investigated variation in both the shape and size of archaeological specimens
73 (Albrecht et al., 1972; Clément and Leroy-Prost, 1977; Knecht, 1991). However, they
74 searched for patterns of variation through the analysis of the implements' general outline
75 in an attempt to identify the specific forms reproduced by the makers of the Aurignacian
76 projectile points. Consequently, the results obtained necessarily conflated a minimum of
77 two sources of variation, i.e., the range of forms of newly manufactured points and the
78 morphometric variability resulting from their utilization. Shape variation in tools could be
79 caused by a variety of processes. Therefore, given the anisotropic properties of osseous
80 material, one cannot assume every portion of a point would be equally affected by these
81 processes (see below).

82 From an analytical standpoint, with the exception of the works by Turk (2002,
83 2003, 2005), these studies were carried out prior to, or during, the development of
84 modern landmark-based geometric morphometrics (Bookstein, 1989, 1991, 1996, 1997;
85 Moyers and Bookstein, 1979). The theoretical and methodological advances made in this
86 field of investigation over the last two decades now bring forth new prospects to reassess
87 the morphometric variability of Aurignacian osseous projectile points with the aim of
88 identifying the shapes that were reproduced by the prehistoric populations. In the present
89 paper, the concept of shape modularity (Adams, 2016; Klingenberg, 2008, 2009;
90 Klingenberg and Marugán-Lobón, 2013) is used to analyze the outline of Aurignacian
91 split- and massive-based points from 38 European sites. This concept is useful to identify
92 the point of demarcation between distinct techno-functional units, or components, on the
93 shape of an implement of composite technology. The morphometric variability of each

94 component can then be interpreted as a result of functional and/or stochastic processes in
95 the light of technological and experimental data. Focusing on the component that is
96 mainly affected by stochastic processes allows the identification of eight proximal shapes
97 for split-based points and two proximal shapes for massive-based points. The geographic
98 distribution of these shapes is investigated to assess patterns of regionalization.

99

100 **Research background**

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

124 the points. Finally, the factors causing shape variation are summarized as well as the
125 criteria that allow identifying their respective effect on the archaeological record.

126 Applying geometric morphometrics methods to the analysis of Aurignacian osseous
127 projectile points constitutes a real challenge given their simple outline and the
128 fragmentary state of most specimens. On the one hand, the simple outline limits the
129 number of Type I landmarks (Bookstein, 1991; Mardia and Dryden, 1989) that can
130 possibly be recorded, i.e., the loci equivalent to anatomical features present on every
131 outline such as the distal tip, the basal end, or the points delimiting the maximum width
132 of the artefact. In most cases, only the latter two landmarks are available, i.e., the two
133 landmarks that are placed on either side of the point of maximum width (see Lycett et al.,
134 2006 for a discussion on the lack of Type I landmarks on archaeological artefacts).
135 However, their position at either end of one of the tool's major axis, i.e., the maximum
136 width, prevents the precise definition of homologous sliding semi-landmarks (Perez et al.,
137 2006) along the outline of the point. On the other hand, given that most specimens are
138 damaged, with distal and/or proximal fractures, it is not possible to accurately estimate
139 the percentage of completeness of a point. Consequently, both semi-landmark methods
140 (Bookstein, 1997) and Fourier transform methods (Haines and Crampton, 2000) cannot
141 be used for simple shape comparison.

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

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

182 Shape modularity is founded on the ‘theory of *nearly decomposable* systems, in
183 which the interaction amongst the subsystems are weak, but not negligible’ (Simon,
184 1962, p. 474). In biology, modularity refers to cases where the landmark configuration of

185 an organism can be split into subsets of landmarks, or modules, and where patterns of
186 variation are unevenly distributed between subsets; covariation is greater for landmarks
187 belonging to a given module while being weaker for landmarks across modules
188 (Klingenberg, 2008, 2009; Klingenberg and Marugán-Lobón, 2013). These modules are
189 usually interpreted as a consequence of developmental, functional, or evolutionary
190 processes. Likewise, from a technological perspective, the components of a modular
191 structure should be functionally distinct and their variability is expected to be relatively
192 independent from one another. Shape modularity has seldom been solicited in
193 archaeological studies of material culture. Following Cardillo's (2010) suggestion that
194 lithic points could be divided into a set of modules based on morphological or
195 technological criteria, González-José and Charlin (2012) used shape modularity to assess
196 functional variability of lithic points from Late Holocene contexts in southern Patagonia,
197 while de Azevedo et al. (2014) highlighted differences in the patterns of maintenance of
198 these same points according to their function. In the present paper, the first application of
199 shape modularity in osseous technologies is presented for two types of Aurignacian
200 projectile points, i.e., the split- and massive-based points. The aim is to identify the
201 shapes that were considered fit for hunting and reproduced by the makers of these
202 technologies. Such investigation requires the identification of the techno-functional unit
203 that is more likely to have retained the original shape reproduced during the manufacture
204 of an armature in spite of the various episodes of use, damage, reshaping and recycling it
205 underwent prior to being lost or discarded at a site.

206 Experimental data on the use and efficiency of osseous projectile technologies
207 tends to demonstrate that the distal portion of an osseous armature is more prone to
208 damages resulting from its utilization than the proximal portion of the object (Bradfield,
209 2013; Bradfield and Brand, 2013; Doyon and Katz Knecht, 2014; Knecht, 1991, 1997;
210 Newcomer, 1974; Pétilion, 2006). This differential breakage pattern is best explained by
211 the mechanical properties of the raw material itself (Christensen, 2004; Doyon and Katz
212 Knecht, 2014; Knecht, 1991, 1997; Newcomer, 1974) and has implications on how to
213 study the shape of these tools. Assuming that most Aurignacian projectile points
214 discarded at sites had reached their optimal threshold in terms of perceived utility and
215 efficiency (Doyon, 2017b, p. 233), the original rules of production guiding the shaping of

216 the implements' distal portion are likely to have disappeared from the archaeological
217 record. Some archaeological specimens, however, also attest to the repair of the damaged
218 proximal portion and the recycling of fragmented points (Tejero, 2014). The effects of
219 the maintenance of split-based points, for example, are mainly visible on their cross-
220 section morphology, i.e., the original elliptical section becomes more biconvex, while
221 their maximum width and thickness remain more or less the same as these variables were
222 likely determined by the size of the – presumably wooden – shaft to which they were
223 attached. Furthermore, the maintenance of a point's proximal portion may cause its edges
224 to become slightly asymmetrical, albeit not sufficiently deformed to make the original
225 outline unrecognizable (Tejero, 2016). Therefore, the search for original shapes should
226 focus on the hafted proximal end of the point, as this portion is less likely to have
227 undergone substantial modifications over time (see Ahler and Geib, 2000; Smith and
228 DeWitt, 2017; Thomas et al., 2017 for similar arguments in the case of Paleoindian fluted
229 points from North America).

230 Apart from the extent of reworking it underwent, the proximal shape of
231 Aurignacian projectile points could vary due to the type of raw material used for their
232 manufacture, the alteration incurred following their post-deposition, the intended function
233 of the tool, or a number of learning and population-regulated processes, e.g., socially
234 shared rules of production, skill, copying errors, and cultural drift. Associated evidence
235 from the archaeological record can guide the interpretation of patterned variations as a
236 result of either of these processes; each factor is reviewed below. The mineral and
237 organic composition as well as the structure of the osseous material vary between antler,
238 bone, and ivory (see Christensen, 2004; Knecht, 1991 for a review). This variation could
239 impose some limitations on the sequence of techniques that is applied during the
240 manufacture of a particular tool type. Differences in manufacturing behavior could also
241 be, in some cases, a proximal factor that underlies differences in shape of a given tool
242 type (e.g., Schillinger et al., 2017). Therefore, one should seek for correlations between
243 raw material and the tool type, its shape, or both to assess its effect on morphometric
244 variability. Post-depositional alterations could either result in the damage or the
245 deformation, i.e., compression or bending, of the outline of a bone tool given the
246 anisotropic properties of this raw material. Ideally, these alterations should be identified

247 and the specimens, or the landmarks, affected by this process should be removed from an
248 analysis that aims to document the patterned variation of newly made tools. If function is
249 a primary driver for differences in weapon form, one should expect to find discrete
250 associations between the shape of the tool and either the type of prey that was hunted, the
251 ecological niches in which the points were recovered, or some evidence of its use in
252 different tasks such as penetrating, slicing, or cutting. However, with regard to this last
253 factor, and unlike their lithic counterparts, the edges of osseous points do not have
254 lacerating properties. The smooth surfaces of Aurignacian implements suggest their
255 intended function was primarily to pierce the skin and penetrate sufficiently deep into the
256 prey to perforate the internal organs and cause a lethal hemorrhage (Knecht, 1991, 1997).
257 Therefore, in the present study, functional associations will only be sought between the
258 artefact shape and the type of prey as well as the ecological niches in which the armatures
259 were used.

260 Included amongst the learning and population regulated processes are socially
261 shared rules of production (Lycett and von Cramon-Taubadel, 2015; Schillinger et al.,
262 2014), skill (Eerkens, 2000; Ingold, 2002; Minar, 2001), copying errors (Eerkens and
263 Lipo, 2005; Gandon et al., 2014; Hamilton and Buchanan, 2009; Schillinger et al., 2014),
264 and cultural drift (Binford, 1963; Koerper and Stickel, 1980). Socially shared rules of
265 production can be identified through the occurrence of a weapon form at multiple sites of
266 comparable age. The geographic distribution of these forms would signal the territory
267 inhabited by the populations amongst which these rules were shared. Differences in skill
268 are more likely to result in the variation of a given shape rather than in the long-lasting
269 production of an altogether new weapon form. Copying errors, on the contrary, are
270 cumulative by nature. If this process is in action, one should expect to identify gradual
271 trends in time from an original to a new tool shape. Likewise, if cultural drift is
272 responsible for the patterned variations, gradual trends should be observed in both space
273 and time. Lastly, morphological differences could potentially be the result of temporal
274 drift (e.g., Rigaud et al., 2015, 2018). In this scenario, stratified sites should testify to the
275 appearance and disappearance of specific artefact forms through time. However,
276 chronology, in and of itself, does not provide an explanation as to how and why
277 morphological variability was introduced in the production sequence. Therefore,

278 temporal drift must be explained by other processes such as copying errors, cultural drift
279 or changes in the favored rules of production.

280

281 **Materials and Methods**

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

298 A 36-segment polar grid was superimposed on photographs of the plan view of the
299 superior aspect of the artefacts, i.e., the aspect where the antler spongiosa, or traces of it,
300 is not present, in order to record the landmarks that summarize their shape configuration.
301 The origin of this grid was aligned at the intersection between the main axes of the tool,
302 i.e., the maximum length and width (Fig. 1a). Following the superimposition of the grid,
303 the digitization of the shape configuration consists of recording 36 landmarks for each
304 specimen. The use of photographs to record landmarks implies the shape of the objects is
305 modeled in only two dimensions. The comparison of 3-dimensional shapes from 2-
306 dimensional landmark configurations can indeed result in the loss of information on the
307 overall morphometric variability. However, this loss is not statistically significant for
308 almost flat objects (Velhagen and Roth, 1997), which is the case for Aurignacian osseous

309 projectile points. Therefore, the primary assessment of the morphometric variability of
310 these implements focused on the outline of the tool. The armature's thickness was later
311 considered in the clustering method as a means to identify the proximal shapes
312 reproduced in the manufacture of projectile points (see below). Landmarks were recorded
313 at the intersection of a grid segment and an intact portion of the point's outline in order to
314 *de facto* rule out variability that could be attributed to post-depositional processes. The
315 first landmark corresponds to the right end point of the maximum width and the 35
316 remaining landmarks are consecutively recorded clockwise from one grid segment to the
317 next. The same procedure was carried out for the damaged points with the exception that
318 missing landmarks were given [NA,NA] coordinates in the *.nts file where the shape
319 configurations were saved (Fig. 1b). The data was subsequently uploaded in R-CRAN (R
320 Development Core Team, 2008) using the '*geomorph*' package for morphometric
321 analysis (Adams et al., 2016; Adams and Otárola-Castillo, 2013). No attempt to
322 interpolate missing landmarks was undertaken in the present study. However, the sample
323 size varies from one analysis to the next. For each analysis, the specimens included are
324 those with known coordinates for each landmark considered (see below).

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

340 relative to the others included in the subsample. From the GPA, two variables can be
341 extracted. The first corresponds to the mean shape configuration and the second is the
342 specimens' centroid size, i.e., the sum of squared distances of a series of major landmarks
343 to their common centroid (Bookstein, 1991).

344 Testing for shape modularity implies calculating a covariance ratio CR of a
345 hypothetical modular configuration and comparing it to a number of randomly generated
346 ones. Non-parametric testing allows for the quantification of CR and its associated p -
347 value. The null hypothesis of an equal variation in the covariation matrix is rejected at α
348 = 0.05 when CR is lower than 1 (Adams, 2016). The rejection of the null hypothesis
349 entails the techno-functional components of a point should be studied separately in order
350 to assess their respective contribution to the overall morphometric variability. For this
351 test, only complete specimens with data for the 36 landmarks are selected ($n = 111$; split-
352 based points: $n = 64$; massive-based points: $n = 47$).

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

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

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

382

383 **Results**

384 In the sample considered for the present study, more than one fifth of the points are
385 complete (split-based points: 21.8%; massive-based points: 22.0%; Tab. 1). Proximal and
386 distal damages are respectively present on 18.3% and 27.0% of split-, and 1.9% and
387 47.5% of massive-based points (Tab. 2). Both proximal and distal damage was recorded
388 on 47.0% of split- and 41.9% of massive-based points. The remaining portion of the
389 sample shows lateral damage, sometimes in combination with proximal and/or distal
390 damage (split-based points: 7.8%; massive-based points: 8.8%). Aside from three
391 specimens, i.e., two made of bone and one made of ivory, all split-based points are made
392 of antler. Massive-based points were predominantly produced from antler (73.1%) but
393 also from bone (21.5%) and ivory (5.4%). In Western Europe, all massive-based points
394 were made of antler with the exception of one specimen made of bone from La Ferrassie.
395 In Central Europe, the three raw materials were used for the manufacture of this tool
396 type. However, points made of bone predominantly come from Potočka zijavka and those
397 in ivory are mostly found at Mamutowa.

398 The modularity test (Fig. 2) produces significant results for both split- (observed
399 $CR = 0.885$; $p = 0.001$) and massive-based points (observed $CR = 0.92$; $p = 0.038$). These
400 results indicate the patterns of covariation are unevenly distributed between the proximal
401 and the distal portions of complete specimens, which provide quantitative support to

402 technological and experimental observations. As suggested by the overlap of the traces of
403 manufacture, the maximum width is identified as the point of demarcation between these
404 two techno-functional components (Fig. 1d). The maximum width itself belongs to the
405 distal component of the armature. The uneven distribution of the patterns of covariation
406 between both techno-functional units implies different processes were likely responsible
407 for their respective variability. In order to avoid conflating these factors in the following
408 analysis, shape variation for each techno-functional unit is addressed separately.

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

420 For the distal portion of the points, the first two principal components explain
421 95.23% of the total variation (Fig. 4a). The first principal component synthesizes the
422 maximum width relative to the distal length combined with the morphology of the tip
423 (PC1: 91.22%), while the second relates to the lateral asymmetry of the distal portion
424 (PC2: 4.01%). Both types are considerably overlapping, although split-base points tend to
425 have a smaller distal length relative to their maximum width compared to massive-based
426 points. Specimens made of bone or ivory display principal components' values within the
427 range of variation observed for antler armatures (Fig. 4b).

428 The hierarchical clustering procedure identifies eight shape clusters (S01 to S08)
429 for split-based points (Fig. 5–6). Specimens assigned to distinct clusters differ both in
430 terms of their size and their shape. Seven shape clusters (M01 to M07) are identified for
431 massive-based points when applying the same method (Fig. 7–8). However, with the
432 exception of the specimen assigned to the cluster M04, the implements belonging to the

433 six other shape clusters show substantial morphological overlap (Fig. 7b), and only differ
434 from one another when the size of the armatures is considered (Fig. 7c).

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

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

453

454 **Discussion and Conclusion**

455 The present study represents a first attempt to apply landmark-based geometric
456 morphometrics and use the concept of shape modularity to analyze the morphometric
457 variability of osseous projectile technology. The results obtained from the shape
458 modularity test supports the idea that Aurignacian populations conceived their osseous
459 armatures as tools combining two distinct, yet complementary, components fulfilling
460 different functions. The shaping of either component clearly followed specific guiding
461 principles. While similarities are observed for the shape of the artefacts' distal portion,
462 both types differ significantly with regard to the morphology of their hafted portion. The
463 application of geometric morphometrics to explore the variability of the hafted portion

464 allows the identification of the proximal length relative to the maximum width as the
465 principal component of their shape variation. This result has important implications for
466 our understanding of Aurignacian osseous projectile technology. If the points' maximum
467 width and thickness were constrained by the cross-section's dimensions of the wooden
468 shaft on which they were attached (Tejero, 2014, 2016), the points' proximal length, and
469 their proximal morphology, likely varied based on the conception prehistoric artisans had
470 of a suitable hafting mechanism. Reworking of damaged proximal portions seems only to
471 have marginally affected the morphology of the points as attested by the low percentage
472 of variation resulting from lateral asymmetry.

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

485 The geographic distribution of split- and massive-based points' proximal shapes
486 highlights conspicuous differences that are best understood when two technological
487 aspects are considered, i.e., raw material selection and the complexity of the reduction
488 sequences for the manufacture of these implement types. The split-based points found in
489 the archaeological record were almost exclusively made of antler. Given its higher
490 percentage of organic matrix compared to bone or ivory, its microstructural organization,
491 and its ensuing mechanical properties (Albrecht, 1977; Christensen, 2004; Currey, 1979,
492 1984, 1999, 2002; Knecht, 1991), antler is more suitable for the manufacture of the
493 proximal split than the two other raw materials. This step of the reduction sequence
494 constitutes a critical moment (*sensu* Lemonnier, 1976) in the manufacture of this tool

495 type, and it requires a certain level of mastery. Indeed, failure to produce a proximal split
496 would result in the loss of a suitable blank, or of a substantial portion of it, for the
497 manufacture of a point. Use-wear studies combined with experimental replications
498 suggest the production of a proximal split could be achieved through the application of a
499 number of processes such as cleaving the blank (Knecht, 1989, 1991, 1993) or the flexion
500 of the blank subsequent to its incision (Nuzhnyi, 1998; Tartar and White, 2013). The
501 selection of a unique raw material to be transformed following a given sequence of
502 techniques in order to achieve particular morphologies that show patterns of
503 regionalization over vast territories suggests that somewhat strict rules of production
504 guided the Aurignacian makers of split-based points. On the contrary, massive-based
505 points could be made of antler, bone, or ivory, and the shaping of their hafted proximal
506 portion can be achieved simply by scraping. Furthermore, the geographic distribution of
507 the proximal shapes identified in the present study is mainly characterized by their
508 regional or local aggregation. Together, these observations indicate an increased
509 flexibility in the rules of production of this tool type compared to those of the split-based
510 points.

511 If utilization and resharpening of the points account for the morphometric
512 variability of their distal portion (Doyon and Katz Knecht, 2014; Liolios, 1999; Tejero,
513 2014; Turk, 2002, 2003, 2005), other factors responsible for the patterned variations
514 observed on the proximal portion of Aurignacian osseous armatures must be considered.
515 Raw material availability could explain the predominance of bone points at Potočka
516 zijavka and of ivory points at Mamutowa. Indeed, the numerous cave bear remains at
517 Potočka zijavka indicate this locality served as hibernating den for this animal. It
518 remains, however, difficult to assess if Aurignacian groups visited this site to kill
519 hibernating prey at a time when they were most vulnerable (e.g., Withalm, 2004), or if
520 they exploited carcasses of animals that died of natural causes. In the case of Mamutowa,
521 this site is located in a region where mammoth hunting and exploitation by Aurignacian
522 populations are documented (Vercoutère and Patou-Mathis, 2010). Nonetheless, Potočka
523 zijavka yielded specimens with proximal shapes highly similar to those produced in
524 antler found at La Ferrassie. On the other hand, although M07 was exclusively found at
525 Mamutowa, this shape corresponds to a variant of one of the main proximal shapes

526 identified for massive-based points. As mentioned above, these variants mainly differ
527 when the implement's size is considered. Consequently, in addition to having an effect on
528 the type of projectile point to be manufactured, it appears the raw material mainly
529 determined the size of massive-based points but had little bearing on their proximal
530 morphology.

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

553 The effects of learning and population regulated processes on the morphometric
554 variability of split- and massive-based points are somewhat difficult to assess at this
555 point. The three principal components of variation identified for the proximal portion of
556 the implements in the present study leave unexplained only a small percentage of the

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

576 Despite the limitations imposed by the archaeological record, which prevent us
577 from precisely distinguishing the relative effects of the aforementioned processes on the
578 morphometric variability of Aurignacian osseous projectile points, the ethnographic
579 literature highlights the fact that the adoption of a particular hunting technology results
580 from a number of complex decisions, and that the knowledge surrounding the
581 manufacture and use of these technologies is socially shared (Churchill, 1993; Ellis,
582 1997). This knowledge includes the type of projectile that should be manufactured, the
583 ways in which they should be used, but most importantly the technological sequence
584 leading to their production. It should be stressed that variations in the proximal shape of
585 Aurignacian armatures perhaps originated from minute differences in the manufacturing
586 processes of the points, i.e., differences in how an armature should be made in order to be
587 considered fit for hafting and hunting prey, rather than from the imposition of a mental

588 template on the osseous material (*sensu* Schillinger et al., 2017). In this sense, the
589 proximal portion of split- and massive-based points seems to have preserved clues
590 allowing us to identify the socially shared rules of production that guided their
591 manufacture, and therefore, highlights micro-traditions within the Aurignacian
592 technocomplex similar to those recognized from Middle Stone Age contexts in Africa
593 (Archer et al., 2016) and from Hamburgian contexts in northern Europe (Riede and
594 Pedersen, 2018). The differences in the geographic distribution of the proximal shapes of
595 split- and massive-based points are surely informative of population dynamics such as
596 coalescence and fragmentation, similar to those documented from southern Africa
597 throughout the MIS5 to the MIS2 (Mackay et al., 2014). If this is the case, the variability
598 in the proximal shape of massive-based points combined with their respective geographic
599 distribution likely signal convergent solutions to a same problem, i.e., producing a
600 projectile point with a proximal portion that can be easily be shaped without risking to
601 damage the blank in the process. On the other hand, the pattern described for split-based
602 points probably implies more generalized inter-regional group interactions either through
603 the movement of individuals over long-distance or the transfer of complex knowledge
604 across long-distance through short chains of interaction (e.g., Lombard and Högberg,
605 2018).

606 The results and discussion presented here set forth a previously unexplored research
607 perspective for studies on the European Early Upper Palaeolithic. Research conducted
608 thus far on the identification of the social groups within the Aurignacian metapopulation
609 and the extent of their interactions relied on multiple sources of evidence such as the
610 distribution of ornament types (Vanhaeren and d’Errico, 2006) and the technological
611 organization of their manufacture (Heckel, 2018), the geographic distribution of
612 manufacturing techniques for lithic (Bon, 2002; Michel, 2010; Teyssandier, 2007) and
613 bone technologies (Albrecht et al., 1972; Goutas and Tejero, 2016; Knecht, 1991; Liolios,
614 1999; Tartar and White, 2013), bladelet morpho-technology (Le Brun-Ricalens and
615 Bordes, 2007; Riel-Salvatore and Negrino, 2018), as well as lithic raw material
616 procurement strategies (Caux, 2015, 2017; Féblot-Augustins, 1997, 1999, 2009; Grimaldi
617 et al., 2014; Porraz et al., 2010; Riel-Salvatore and Negrino, 2009). By applying
618 geometric morphometrics and the concept of shape modularity to the analysis of

619 Aurignacian osseous projectile points, it is now possible to add the morphometric
620 variability of their proximal portion to this list of evidence that can serve to identify
621 prehistoric group membership. Future research conducted with the aim of finding
622 correlations between these different proxies will undoubtedly be successful in shedding
623 light on the extent of interactions of past populations at a turning point of the European
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625

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638

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1010 **Legends of figures and tables**

1011 Figure 1: a: Polar grid superimposed on a split-based point from Cova de L'Arbreda (the
1012 green line linking landmarks 1 and 19 corresponds to the maximum width; the blue
1013 line linking landmarks 10 and 28 corresponds to the maximum length; the green
1014 crosses indicate where the landmarks were recorded; Scale = 1 cm); b:
1015 Corresponding landmarks coordinates saved in the *.nts file; c: Generalized
1016 Procrustes Analysis (GPA) of the complete split-based points included in the
1017 present study; d: Demarcation between the distal and proximal modules and their
1018 corresponding landmarks.

1019 Figure 2: a: Results of the modularity test for split-based points (observed $CR = 0.885$; p
1020 $= 0.001$); b: Results of the modularity test for massive-based points (observed $CR =$
1021 0.92 ; $p = 0.038$). The black arrows indicate the observed CR value for each sample
1022 considered.

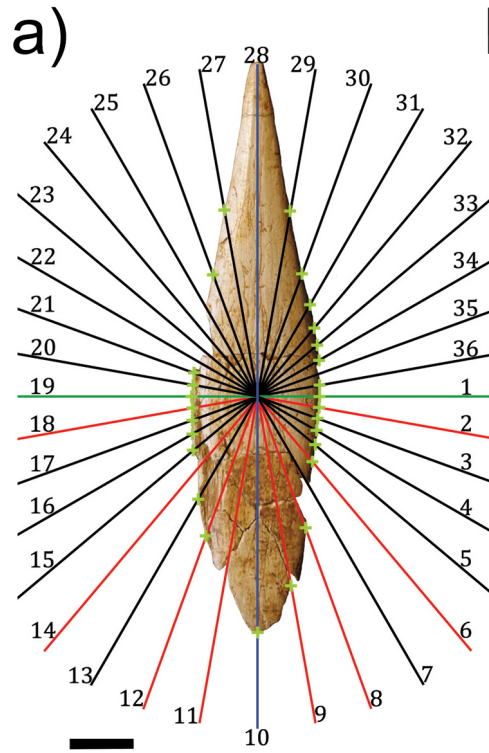
1023 Figure 3: a: Projection of the first two principal components of shape variation for the
1024 proximal portion of split- (red) and massive-based (black) points; b: Projection of
1025 the first two principal components of shape variation for the proximal portion of
1026 massive-based points made of antler (black), bone (red), and ivory (green). *Note:*
1027 Only the specimens with all the landmarks of the proximal module are included in
1028 these graphs.

1029 Figure 4: a: Projection of the first two principal components of shape variation for the
1030 distal portion of split- (red) and massive-based (black) points; b: Projection of the
1031 first two principal components of shape variation for the distal portion of armatures
1032 made of antler (black), bone (red), and ivory (green). *Note:* Only the specimens
1033 with all the landmarks of the distal module are included in these graphs.

1034 Figure 5: a: Projection of the hierarchical clustering tree for split-based points on the
1035 factor map; b: Projection of the first two principal components of shape variation
1036 for the proximal portion of split-based points by shape cluster; c: Range of variation
1037 of the proximal length by shape cluster. *Note:* The horizontal line indicates the
1038 average for the sample considered in the present study.

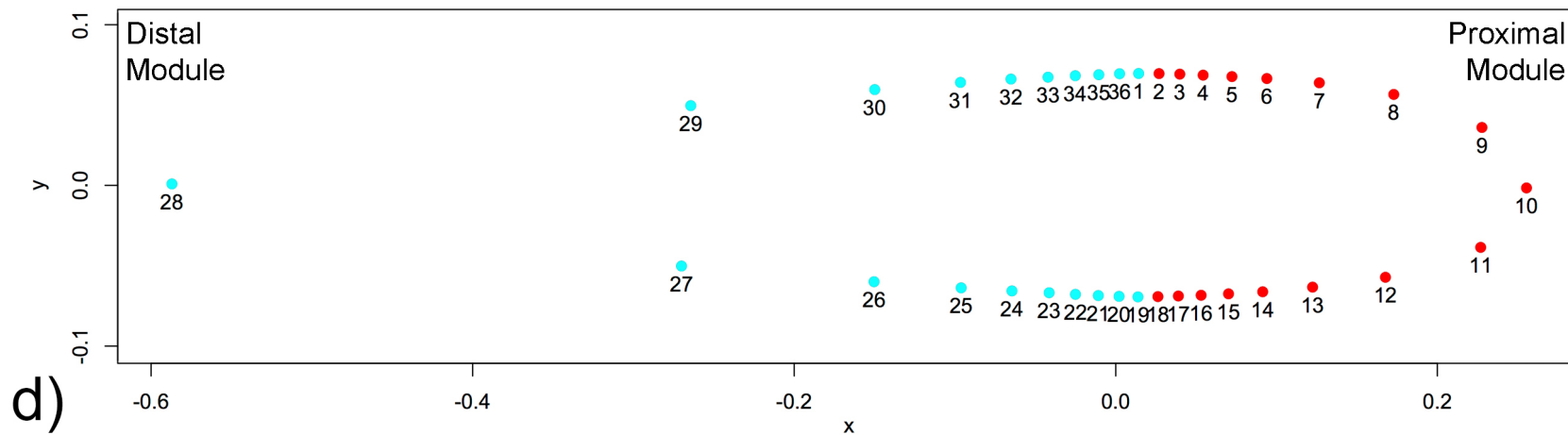
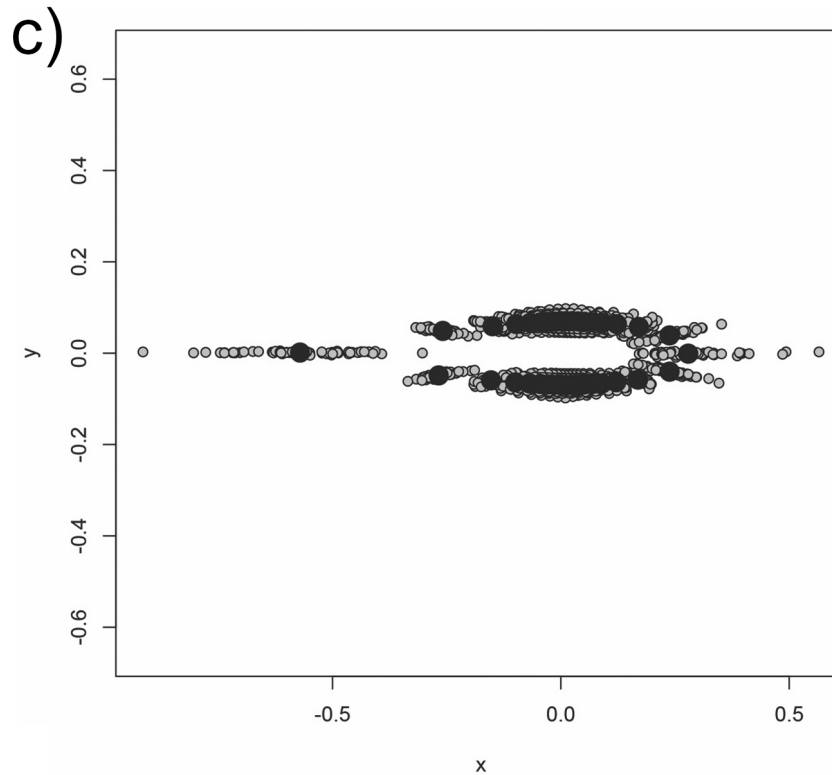
1039 Figure 6: Principal warps for the shape variation of the proximal portion and sample of
1040 split-based points assigned to their corresponding shape cluster. Scales = 1 cm.

1041 *Note:* Grey scaled photographs are part of the Heidi Katz Knecht Collection curated
1042 at the Hominin Dispersal Research Group Laboratory at the University of Montréal.
1043 Figure 7: a: Projection of the hierarchical clustering tree for massive-based points on the
1044 factor map; b: Projection of the first two principal components of shape variation
1045 for the proximal portion of massive-based points by shape cluster. *Note:* The dash-
1046 lined box highlights the data for the shape M04; c: Range of variation of the
1047 proximal length by shape cluster. *Notes:* 1) The horizontal line indicates the
1048 average for the sample considered in the present study; 2) The dash-lined box
1049 highlights the data for the shape M04.
1050 Figure 8: Principal warps for the shape variation of the proximal portion and sample of
1051 massive-based points assigned to their corresponding shape cluster. Scales = 1 cm.
1052 *Note:* Grey scaled photographs are part of the Heidi Katz Knecht Collection curated
1053 at the Hominin Dispersal Research Group Laboratory at the University of Montréal.
1054 Table 1: Contextual data of the sample of points considered in the present study.
1055 Table 2: Percentage and location of damages recorded on the specimens analyzed in the
1056 present study.
1057 Table 3: Over- (black) and underrepresentation (red) of split-based point proximal shape
1058 by region and by site.
1059 Table 4: Over- (black) and underrepresentation (red) of massive-based point proximal
1060 shape by region and by site.

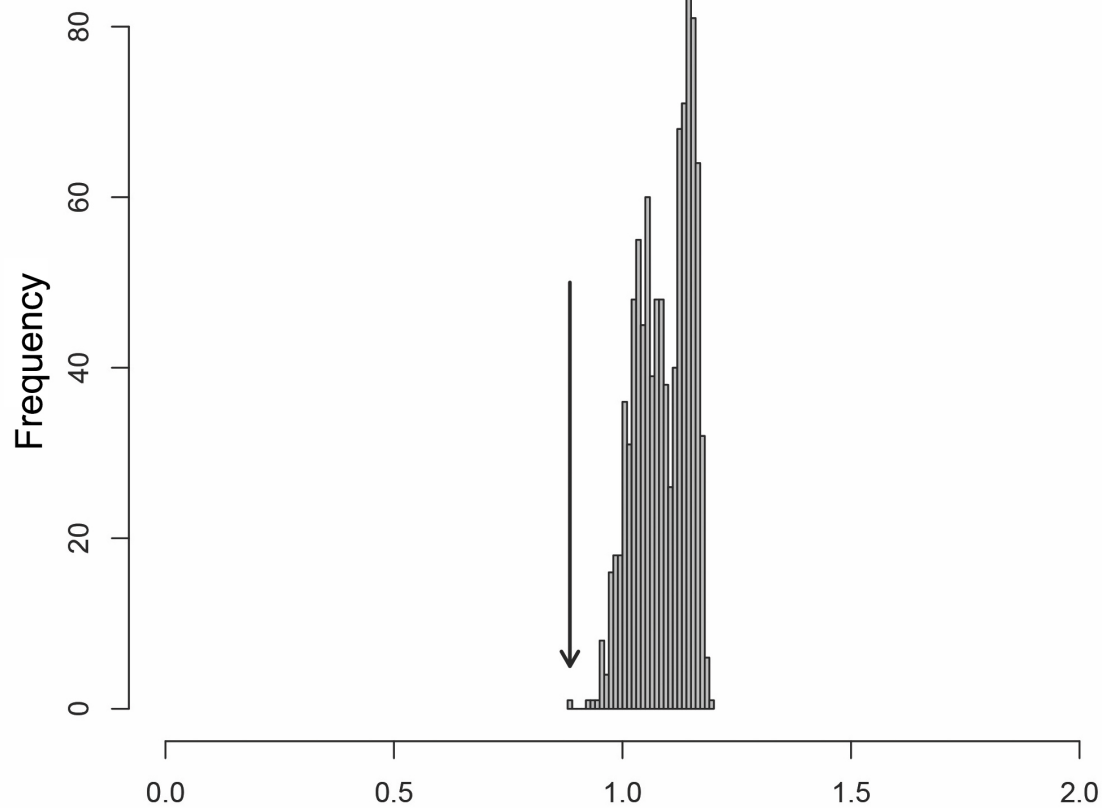


b)

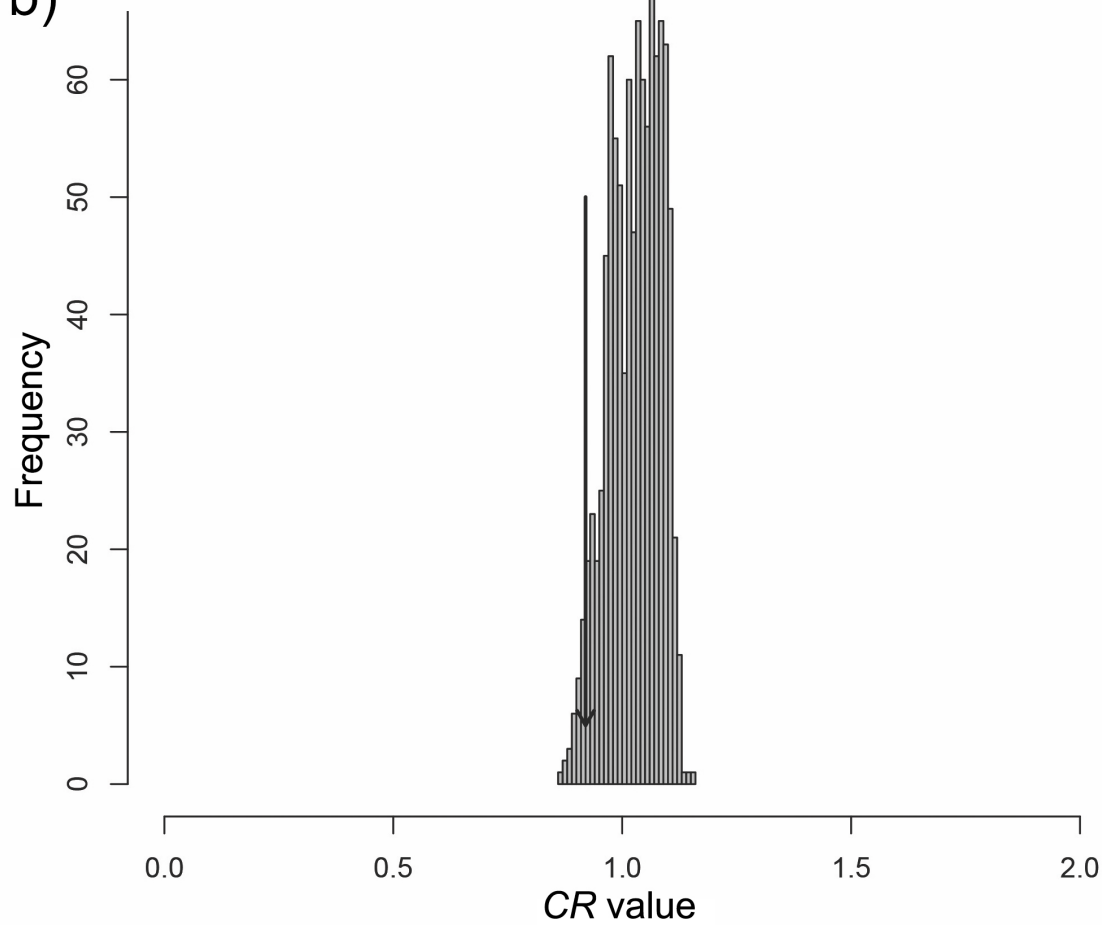
Land_ID	X	Y
1	5.336	5.339
2	5.331	5.165
3	5.318	4.982
4	5.287	4.79
5	5.255	4.572
6	5.215	4.304
7	NA	NA
8	5.117	3.201
9	4.858	2.402
10	4.341	1.716
11	NA	NA
12	3.561	3.183
13	3.44	3.767
14	NA	NA
15	3.365	4.511
16	3.338	4.756
17	3.333	4.965
18	3.333	5.159
19	3.329	5.338
20	3.342	5.516
21	3.356	5.699
22	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



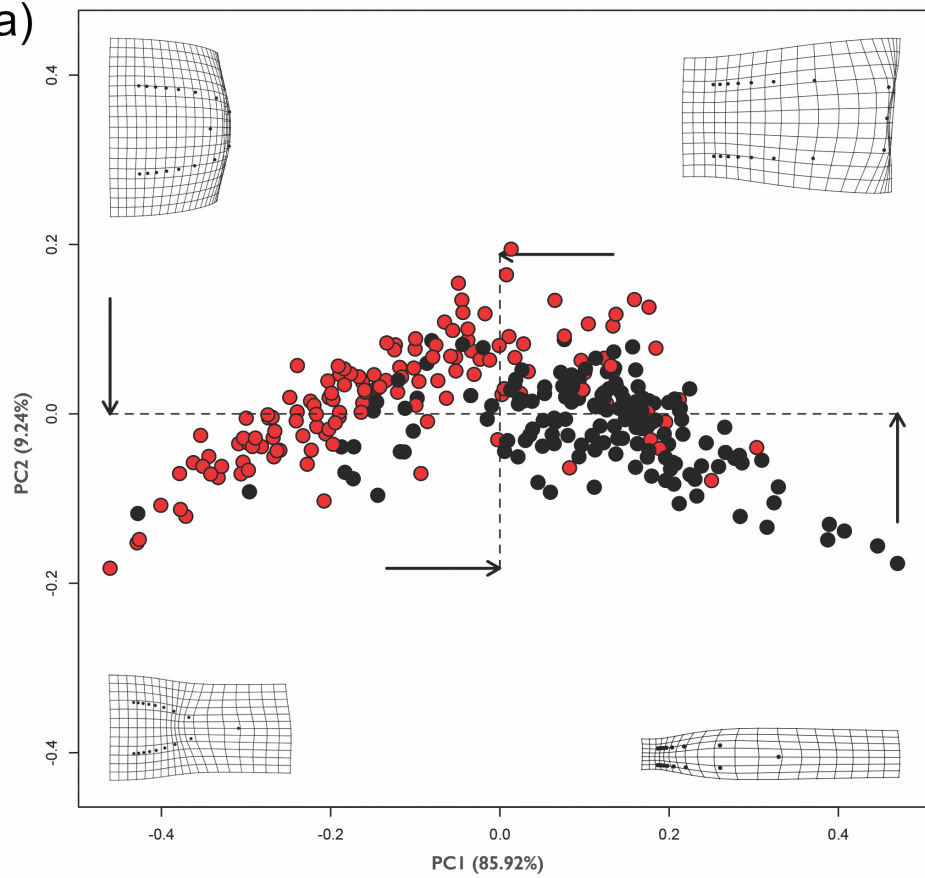
a)



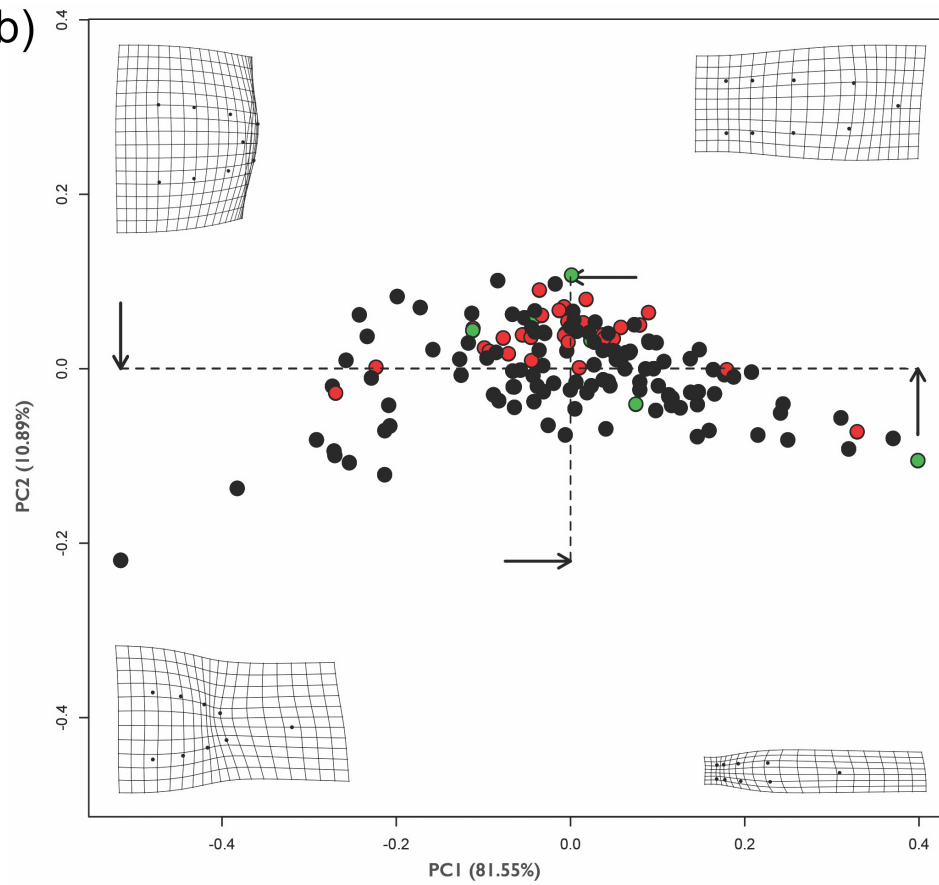
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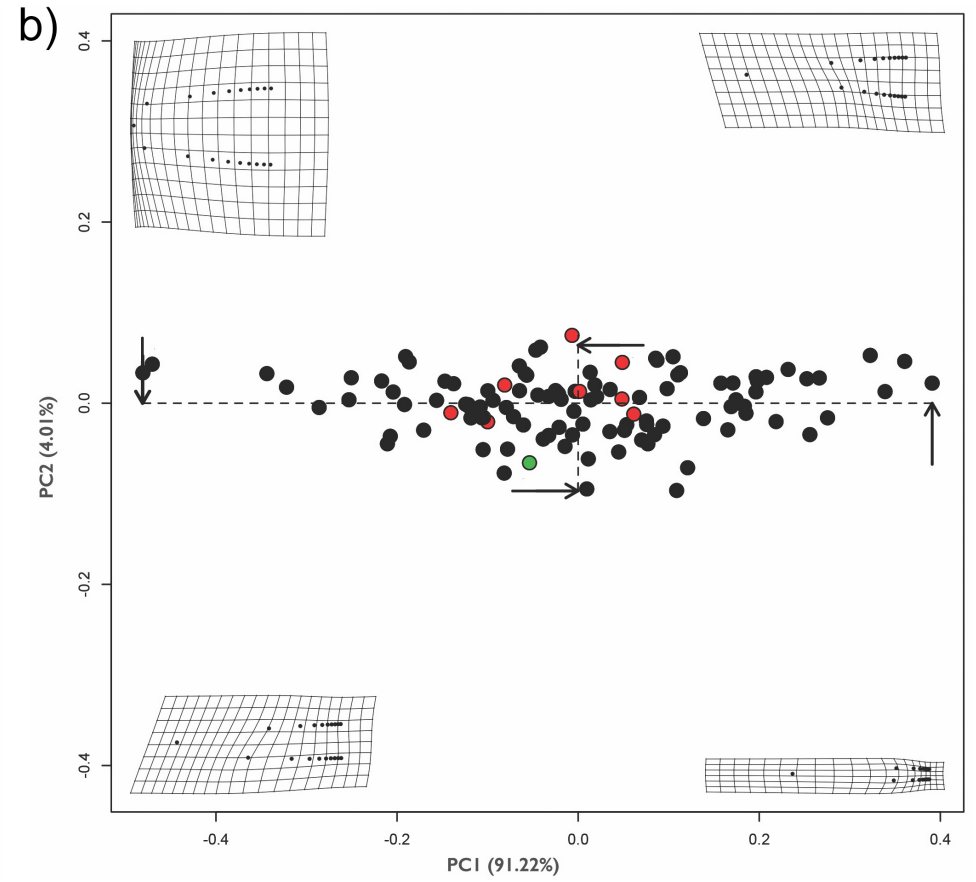
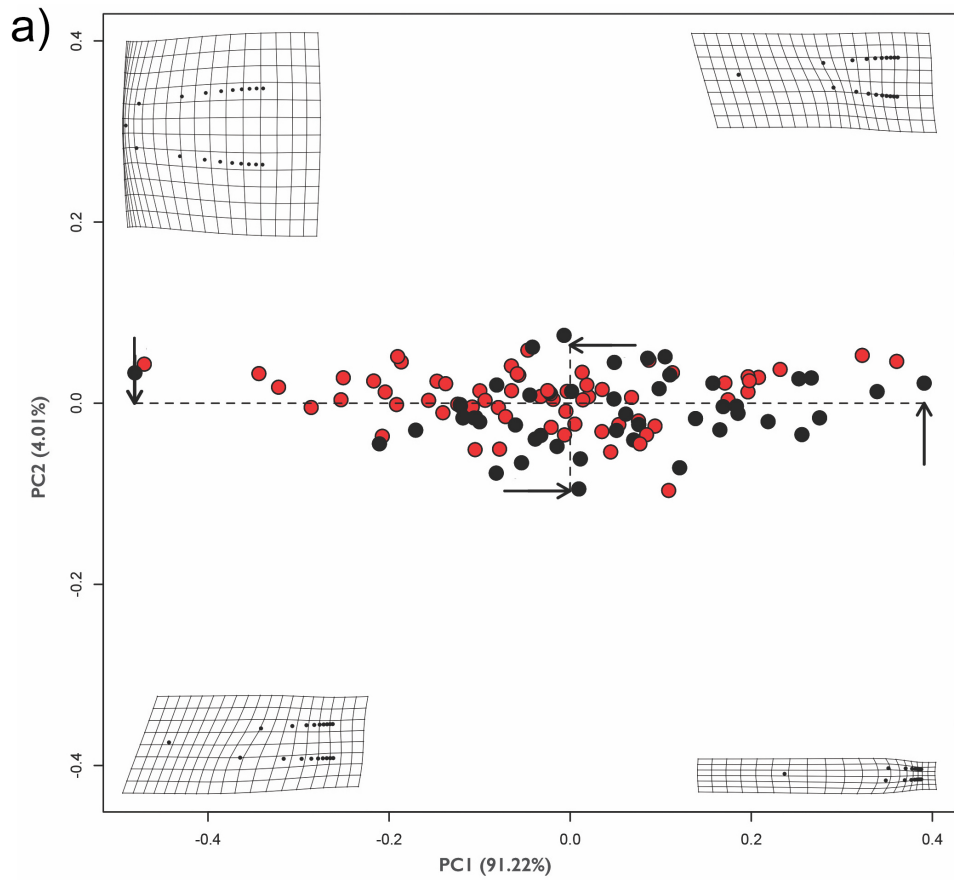


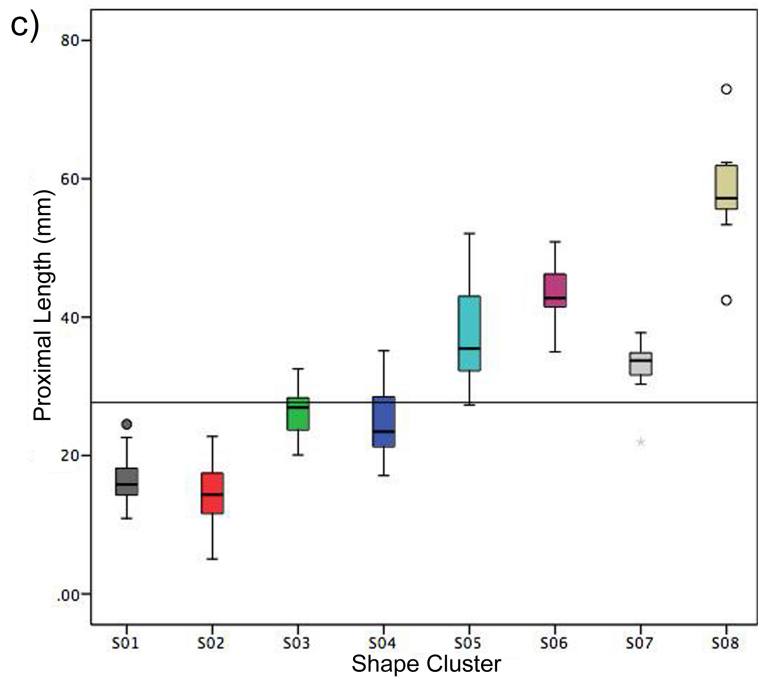
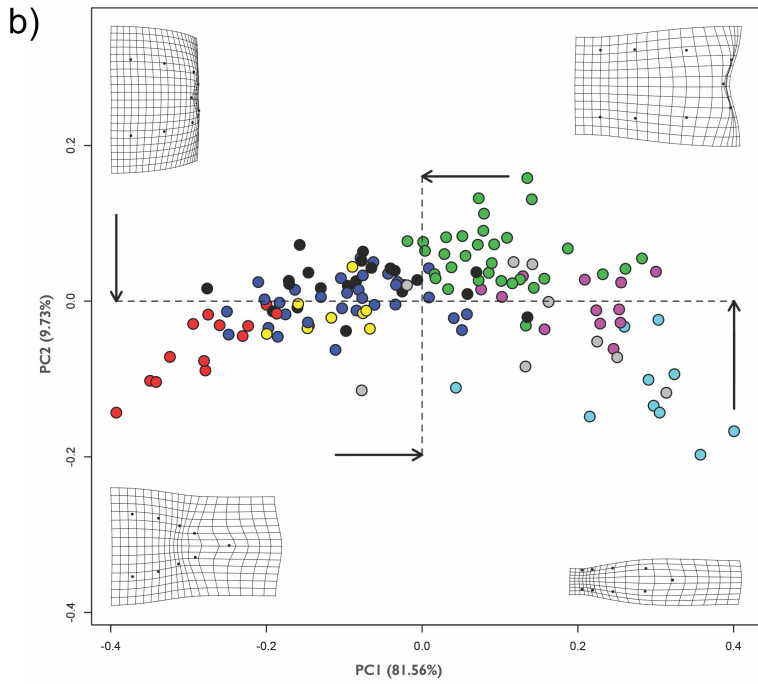
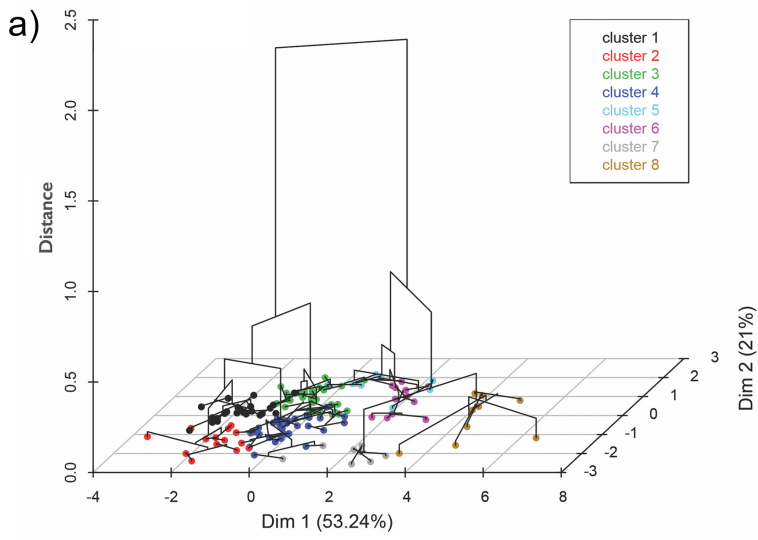
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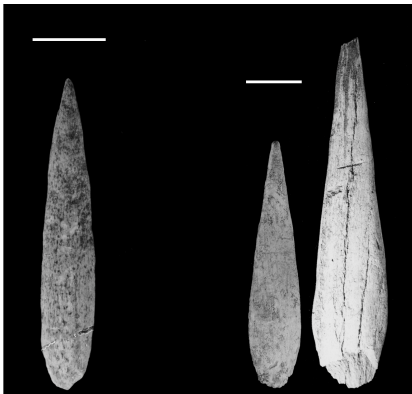
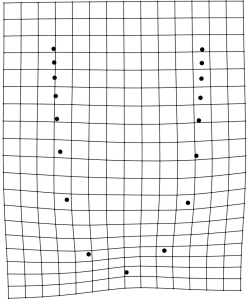
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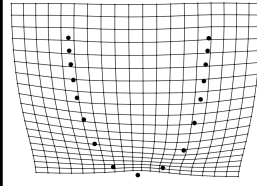




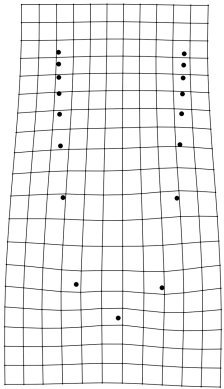
S01



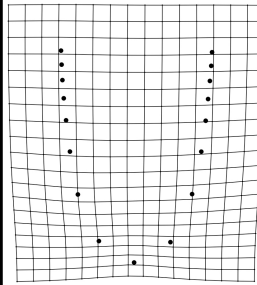
S02



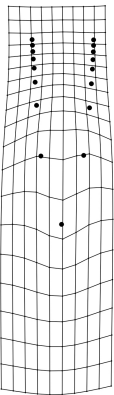
S03



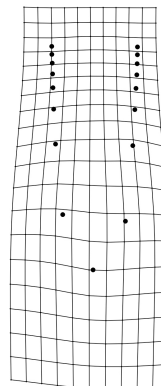
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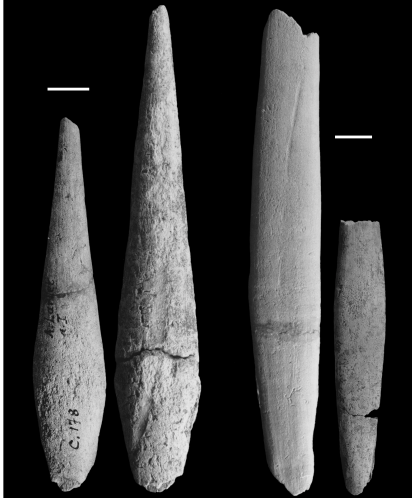
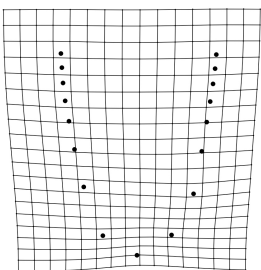
S05



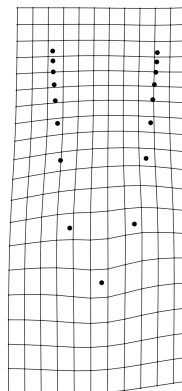
S06

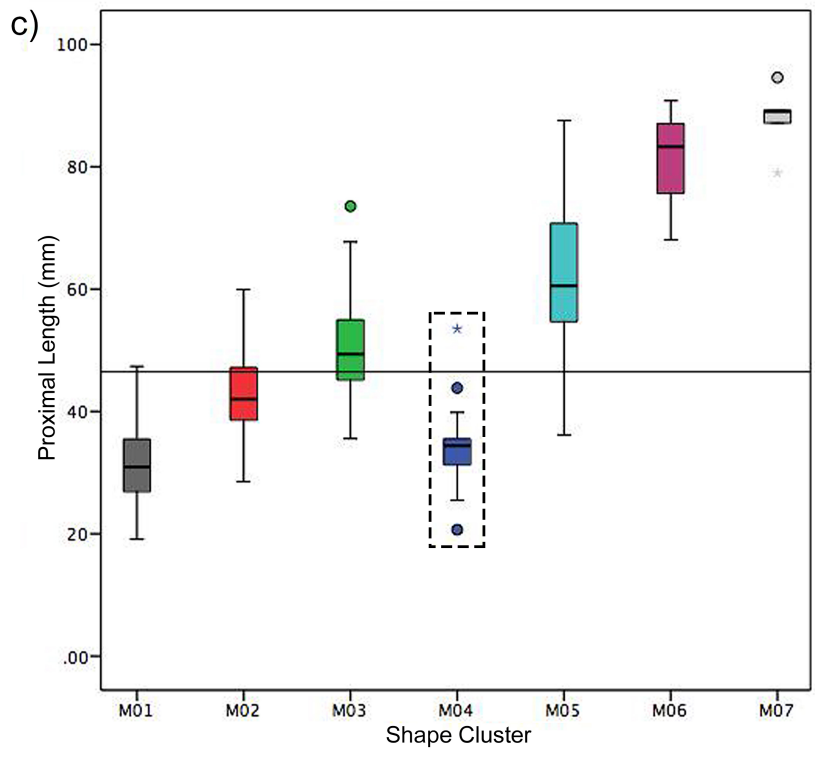
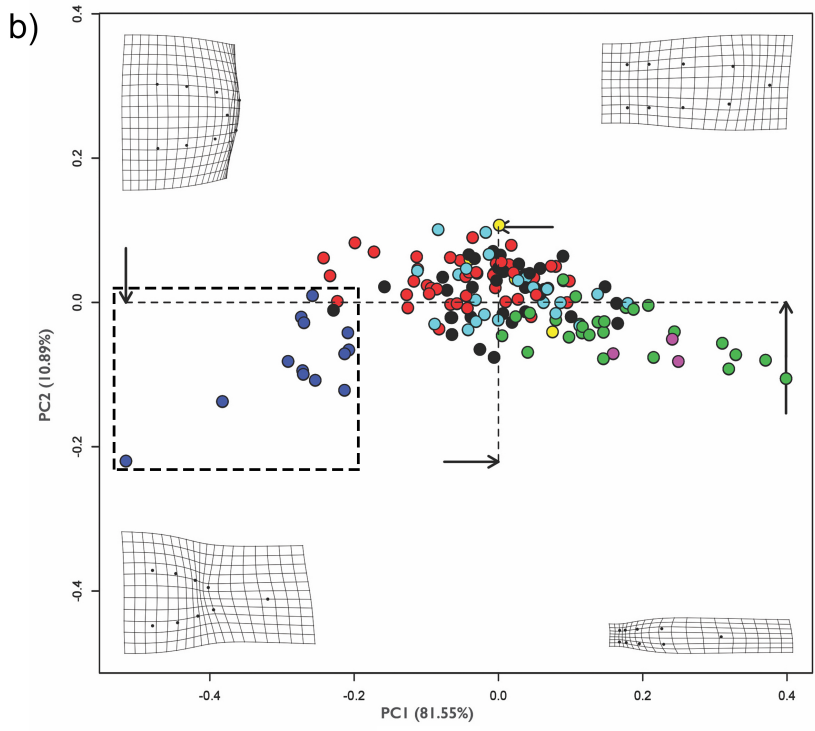
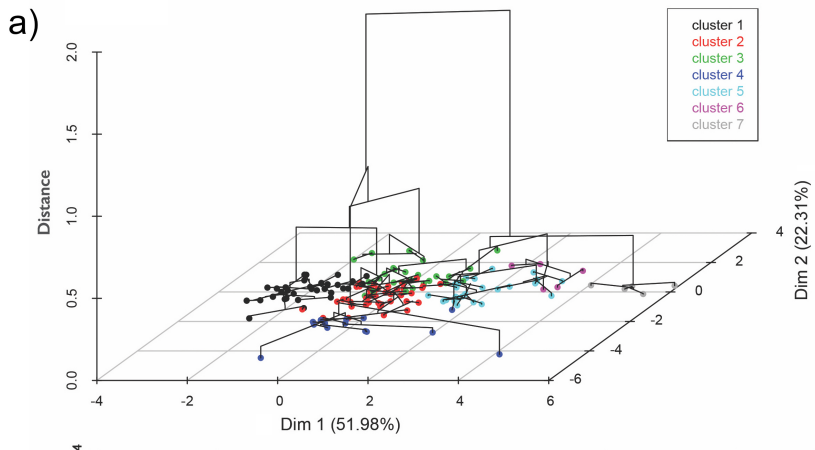


S07

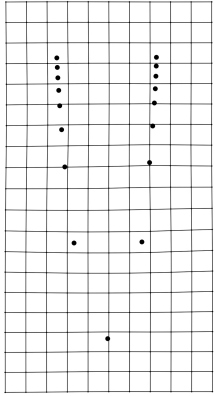


S08

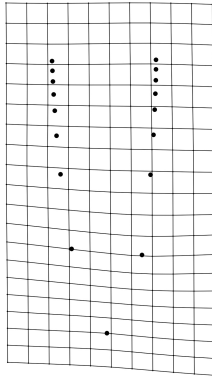




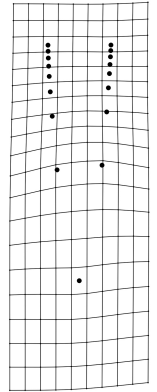
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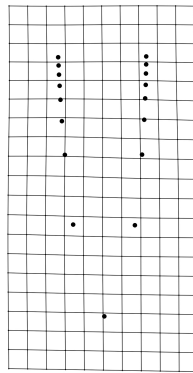
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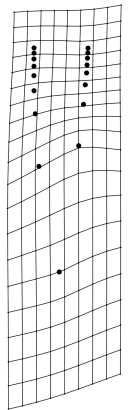
M03



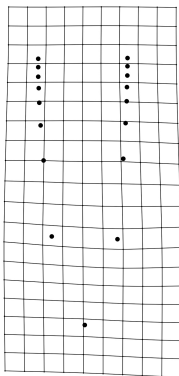
M05



M06



M07



M04

