

1 **Right or left? Determining the hand holding the tool from use traces.**

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29 Abstract:

30 Currently, approximately 90% of the human population is right-handed. This handedness is due to
31 the lateralization of the cerebral hemispheres and is controlled by brain areas involved in complex
32 motor tasks such as making stone tools or in language. In addition to describing the evolution of
33 laterality in humans, identifying hand preference in fossil hominids can improve our understanding
34 of the emergence and development of complex cognitive faculties during evolution. Several fields
35 of prehistory like palaeoanthropology or lithic analysis have already investigated handedness in
36 fossils hominins but they face limitations due to either the incomplete or the composite state of the
37 skeleton remains or to results replication or method application failure. Wear analysis could provide
38 new complementary data about hand preference evolution and the development of certain complex

39 cognitive functions using indirect evidence (use traces, micro-scars in particular) of the hand
40 holding the stone tool during use. Controlled experiment has been carried out in order to establish
41 a reference collection of tools used with the left and tools used with the right hand. Wear analysis
42 was performed on this corpus using “classical” microscopic approach and geometric morphometric
43 analysis. A machine learning algorithm, the k-NN method, was applied to verify if use traces
44 (micro-scars) could help determine the hand holding the tool during use. The best model, based on
45 parameters referring to invasiveness of micro-scars, was able to correctly determine the hand
46 holding the tool with 75% accuracy.

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49 1. Introduction:

50

51 Hand preference is defined by the hand with which an individual performs a specific task
52 (e.g. Annett, 1985; Uomini and Gowlett, 2013). Several studies have demonstrated that hand
53 preference is linked to the lateralization of the cerebral hemispheres and is related to areas of the
54 brain similar to those involved in the control of other essential functions such as language (e.g.
55 Corballis, 2003; Meguerditchian et al., 2013; Stout et al., 2000; Uomini and Meyer, 2013; Willems
56 and Hagoort, 2007). Thus, in addition to describing the evolution of laterality in humans, identifying
57 hand preference in fossil hominids can improve our understanding of the emergence and
58 development of complex cognitive faculties during evolution (e.g. Steele and Uomini, 2009; Stout
59 et al., 2008).

60

61 Currently, between 74% and 96% of the human population preferentially uses the right
62 hand (Annett, 1985; Llaurens et al., 2009; Porac and Coren, 1981). Lefthanders are a minority in
63 all human populations. The highest rate of left-handers recorded in a population is found among
64 the Eipo in Papua New Guinea and is estimated at 26.9% (Faurie et al., 2005).

65 The control of fine manual actions (called “complex” motor actions) is attributed to the left
66 hemisphere which would explain the preferential use of the right hand for this type of action (e.g.
67 Greenfield, 1991; Johnson-Frey et al., 2005; Lewis, 2006; Schluter et al., 2001). Some authors
68 have thus hypothesized the development of a strong manual preference in relation to the
69 manufacture and complexity of tools (Corballis, 1987; Stock et al., 2013; Uomini and Gowlett,
70 2013; Uomini, 2009). Other studies show a greater effect of the nature and demands of the task as
71 well as the type of object involved and the speed of the action (Forrester et al., 2013, 2012, 2011;
72 Pouydebat et al., 2014; Quaresmini et al., 2014; Rogers, 2009). The complexity of the task is
73 therefore probably not the only criterion explaining the emergence of a strong manual preference.
74 Establishing a direct link between strong manual preference and the complexity of (stone) tools is
75 difficult and, so far, concrete archaeological data do not support it. Moreover, few studies highlight

76 the fact that the right hemisphere is also involved and essential in activities such as tool use (Frey
77 and Gerry, 2006; Hartmann et al., 2005; Stout and Chaminade, 2012)

78 In non-human primates, especially great apes, similarly strong lateralization as in humans is
79 missing (Vallortigara and Rogers, 2005). This differs according to the species but also within the
80 same species at an individual level or a population level (Cashmore et al., 2008; Chapelain et al.,
81 2011; Hopkins, 2006; Marzke, 2013; McManus, 2009). Differences in hand preference among non-
82 human primates appear to be due to complex relationships between various factors, such as the
83 environment (life in the wild or captivity), or the complexity and nature of the task (type, speed)
84 (e.g. Fagot and Vauclair, 1991; Hopkins et al., 2011; McGrew and Marchant, 1997; Mosquera et
85 al., 2012; Pouydebat et al., 2014).

86
87 The origin of this peculiarity during human evolution is for the moment unknown. So far,
88 data about fossil hominin hand preference are mainly coming from the skeleton, either directly
89 inferred from forelimb asymmetries or indirectly from the skull. The examination of bone
90 asymmetries on the upper limbs of fossil hominids could deliver direct indications of hand
91 preference. However, as suggested or stated in several studies, observed differences in hand
92 entheses (the surfaces where ligaments are attached on bones) among individuals with the same
93 occupation could be due to numerous variables including inter-individual genetic variability,
94 nutrition or hormone levels, and not just manual activities (Foster et al., 2014; Karakostis et al.,
95 2018, 2017; Karakostis and Lorenzo, 2016).

96 On the other hand, other measurements of upper limb asymmetries have been used to
97 identify human hand preference (Shaw, 2011; Trinkaus et al., 1994). Based on such observation,
98 Sparacello et al. (2017) studied a sample of humeri coming from 107 Late Pleistocene individuals
99 and obtained a distribution of hand preference similar to the distribution obtained with recent
100 human samples (i.e. right: 74.8%, left: 15.0%, ambiguous: 10.3%). Others suggested for example
101 that the articular constraints model could help in the identification of hand preference (Lazenby et
102 al., 2008) or that the analysis of trabecular bone could contribute to the identification of right/left
103 directional asymmetry (Stephens et al., 2016).

104 Moving on to the skull, analyses of cranial endocast asymmetries analyses (e.g. Balzeau et
105 al., 2012; Holloway, 1981; Holloway and De La Costelareymondie, 1982; Poza-Rey et al., 2017)
106 suggested possible relationships between hand preference, endocranial shape, and functional
107 capacities in hominins. Other studies, investigating striations on teeth surfaces, show that even for
108 the Middle Palaeolithic and species such as *Homo erectus* in Asia, or *Homo heidelbergensis* and
109 *Homo neanderthalensis* in Europe, the right hand was already the chosen hand for the majority of
110 individuals, both adults or young individuals (e.g. Bermúdez de Castro et al., 2003, 1988; Condemi
111 et al., 2017; Estalrich and Rosas, 2013; Fiore et al., 2015; Frayer et al., 2012, 2010; Lozano et al.,
112 2009; Poza-Rey et al., 2017; Xing et al., 2017). This could be the case as early as 1.8 Ma as
113 suggested by the study of labial striations on the OH-65 fossil's anterior teeth (Lozano et al., 2017).

114 For younger periods, analysis of wall-paintings and striations on bone tools may give clues about
115 the hand preference of their authors or users respectively (see Spenneman, 1984 for an example
116 concerning Neolithic).

117

118 These studies do not provide data supporting a ratio of left- and right-handers clearly
119 different from now in Prehistory (see Llaurens et al., 2009). However, the more we go back in time
120 the more the application of these methods to extinct hominin species have serious limitations.
121 Relatively bad conservation of skeletal remains often prevents any analysis of traces that are
122 relevant for determining hand preference. Also, apart from the limited number of individuals which
123 could be studied (see table 2.1 of Faurie et al., 2016 for a summary of fossil hominin data for
124 laterality and corresponding references) palaeoanthropology faces the problem of the partial
125 skeleton remains which implies sometimes to study composite anatomical elements composed of
126 bones coming from different individuals (see Cashmore, 2009).

127 On the contrary, stone tools are often abundant in Palaeolithic sites. The data they could
128 provide regarding hand preference are therefore likely to be statistically more representative if
129 whole sets of assemblages are analysed. Different studies have intended to set up a methodology
130 to determine hand preference based on the observation of manufacture features appearing on
131 stone tools (size and shape of flake scatter patterns: Newcomer and Sieveking, 1980; dorsal cortex
132 position: Toth, 1985; occurrence of cortex and relic margins: Bradley and Sampson, 1986;
133 orientation of the cone of percussion: Rugg and Mullane, 2001; resharpening techniques: Cornford,
134 1986; combination of technical features: Bargalló et al., 2018, 2017; Bargalló and Mosquera,
135 2014). These methods give variable results and a recent work from Ruck et al. (2015), applying
136 Toth's, Rugg and Mullane's and Bargalló and Mosquera's methods, showed that these methods
137 were not able to determine the hand holding the hammer for the studied flakes production better
138 than a random guess (see also Patterson and Sollberger, 1986; Pobiner, 1999; Uomini, 2011,
139 2001).

140 The identification of the knapper hand preference based on the spatial organization of
141 debitage remains have also been investigated giving successful results in experimental conditions
142 but the authors highlight the difficulties in applying such method in an archaeological context
143 (Bargalló et al., 2018).

144

145 Some of these methods should be investigated further in order to improve their rate of
146 correct determination and their applicability to archaeological samples. However, producing a
147 stone flake is a quick and punctual activity. Therefore, any variation during this short production
148 moment might modify the types of features appearing on the flake. The poor rates of success in
149 identifying hand preference from patterns in flake production may be due to the high variability of
150 factors influencing the production of any particular flake. On the other hand, a repeated activity or
151 movement is likely to leave behind a stronger "signature" of the hand preference. Therefore,

152 focusing on stone tool use rather than stone tool production could provide better results in
153 identifying hominids hand preference. A handful of studies have attempted to extract hand
154 preference from stone tool use (based on asymmetries of the tool: Brinton, 1896; based on
155 direction of rotation of boring artefacts: Cahen et al., 1979; Cahen and Keeley, 1980; Keeley, 1977;
156 see also Uomini, 2008). Others simply discuss why it is difficult to do so (D'Errico, 1992; Semenov,
157 1970; Weber, 1990). However, to our knowledge, most of them only briefly mention this question
158 and none is based on an experimental reference collection that was statistically tested to allow the
159 identification of specific criteria corresponding to the use of the tool in the right or left hand.

160 Here, we propose to examine if hand preference can be identified from use-wear on stone
161 tools through qualitative (traditional wear observation) and quantitative (measurements and
162 geometric morphometric) wear descriptors. A machine learning algorithm is used for the first time
163 on these data in order to test which of the descriptors is/are the most relevant to recognize the
164 hand holding the tool based on the traces of use.

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166

167 2. Materials and methods

168 2.1. Experimental setup

169 *Tools:*

170 Numerous variables (morphology and raw material type of the tool, worked material,
171 working angle, direction of movement, etc.) can have an effect on the formation of traces on the
172 surface of a stone tool. In order to characterise traces of use related to hand preference but also
173 quantify their variability, it is first essential to limit the effect of these variables and particularly the
174 effect of the form of the tool. Therefore, the form of the tool was standardized using soda-lime
175 glass replicas of a Levallois point (Iovita et al., 2014; figure 1). The use of this glass has the
176 advantage to simulate the type of conchoidal fracture of many raw materials used in prehistory.
177 These artefacts measured 64.5 mm long, 36.5 mm at the maximal width and 6 mm at the maximal
178 thickness, with a weight of 15.8 g on average.

179

180

Figure 1 (1 column)

181

182 *Users:*

183 A total of 20 volunteers participated in the experiment, 10 right-handed subjects (5 women
184 and 5 men) and 10 left-handed subjects (5 women and 5 men). They were beginners in using
185 stone tools; none of them had used prehistoric tools before. The subjects were not aware of the
186 fact that the aim of the experiment was related to hand preference in order to limit modification of
187 their behaviour. Their hand preference was documented along with a number of other variables,
188 including name, age, sex, size, weight, hand size, circumference of the last phalanx of each finger

189 of the hand holding the tool, palm length, palm width, expertise, previous injuries in order to
190 prevent them from identifying the aim of the study.

191

192 *Worked material:*

193 Wooden (*Pinus*) sticks with no bark were provided to each subject. These sticks were of
194 standardized diameter (18 mm) and length (50 cm).

195

196 *Task:*

197 Each individual had to sit on a chair and to saw wooden sticks with three different tools.
198 Each tool was used for a total duration of 20 minutes. The number of strokes was not constrained
199 but number of strokes (forward + backward = 1) per minute was measured during the 5th, 10th and
200 15th minutes in order to approximate the speed of the sawing movement (in mvt/min.) (Whole
201 experiment: min = 98.33 mvt/min., max = 191.33 mvt/min., mean = 135.96 mvt/min., SD = 23.59
202 mvt/min.; for left hand users: min = 98.33 mvt/min., max = 191.33 mvt/min., mean = 141.74
203 mvt/min., SD = 25.37 mvt/min.; for right hand users: min = 100.3 mvt/min., max = 166 mvt/min.,
204 mean = 129.9 mvt/min., SD = 20.41 mvt/min.; see the dataset in supplementary material). Before
205 the experiment proper, a five-minute test was carried out without any instructions to observe how
206 individuals hold and use the tool spontaneously, and to evaluate the constraints of our controlled
207 experiment on the tool grasping mode. The first tool of the proper experiment was used with the
208 only instruction to use the predefined edge. For the second and third tools, the participants had to
209 use the predefined edge and keep the wooden stick horizontal on their knees. Each experiment
210 was recorded individually and documented by one observer using a Samsung NV24HD video
211 camera.

212

213 2.2. Analysis

214 *Description of micro-scars*

215 Each stone tool was observed with a stereomicroscope (Zeiss Discovery V8 with Plan S
216 1.0x objective; FWD = 81 mm; it is equipped with a Touptek camera with a resolution of 5
217 MPixels) before use at 10x (objective FOV = 23 mm) and 80x (objective FOV = 2.9 mm)
218 magnifications. Then, the tools were cleaned (in a solution of DERQUIM LM02 phosphate free
219 neutral soap at 5% in ultrasonic-bath during 15 min), and moulded (using Heraeus PROVIL®novo
220 Light Regular silicone) and casted (using Axson F180 polyurethane resin) to keep a record of their
221 original morphology before use. The tools were then used for a total duration of 20 minutes each.
222 After use, they were cleaned again (same procedure as before use) and observed at 10x and 80x
223 magnifications (with the Zeiss Discovery V8).

224 Micro-scars were documented before and after use on both sides of the tool. Their amount,
225 position (ventral or dorsal face), type, orientation, and (position of) maximum extent on the surface
226 perpendicularly to the edge were recorded (Figure 2). The type of micro-fractures was described

227 following the typology of the Ho Ho Committee (1979): fracture, feathered and step. We added the
228 type “abrupt” to refer to scars which were not straight as a fracture but too steep to enter in the
229 category “feathered”. Three categories were used for the orientation of the scars: perpendicular to
230 the edge, oriented distally (towards the point) and proximally (towards the butt).

231 Statistical tests were performed in R (R Core Team, 2019). As the assumptions of normality
232 and equality of variance for t-test were not met, we used non-parametric Mann-Whitney U tests to
233 verify if the number of micro-scars and if their invasiveness were different depending on the hand
234 holding the tool during use. The Cochran’s rule being respected, we used chi-square test to
235 examine if the type of micro-scars, their orientation and the face where they appeared were
236 independent of the user, of the user’s sex and of the hand holding the tool during use.

237

238

Figure 2 (1 column)

239

Edge modification visualization and quantification

241 Photograph of each tool was taken before and after use. The same camera was not
242 available during the whole study. Pictures were taken with a Nikon D300 equipped with a Tamron
243 16-300mm F/3.5-6.3 Di II VC PZD objective before use (pictures were taken at a focal length of
244 200mm) and with a NIKON 7100 with an AF-D Micro NIKKOR 60mm 1:2.8G ED objective after
245 use.

246 As they were taken with different conditions, the two batches of photos (i.e. from before and
247 after use) were first scaled. They were then binarized with Adobe Photoshop. The Momocs
248 (Bonhomme et al., 2014) and geomorph (Adams et al., 2019) libraries for R were used for the
249 analysis of the shape of the tool edges. The outlines of the tools were automatically extracted from
250 the binarized images. The outlines were then aligned and cut to keep only the area of interest
251 displaying the modifications due to use: the used edge of each tool (Figure 3). The remaining
252 curves corresponding to the used edges of each tool were defined by two landmarks, one at each
253 extremity, and by 1000 equidistant "sliding-semilandmarks" distributed between these two points. A
254 high number of points was chosen because the sought shape differences are due to the micro-
255 scarring of the edges and can be very fine. The space between each "semilandmark" was then
256 optimized by allowing them to slip between the previous and the next point in order to minimize the
257 Procruste distance with the pseudo-homologous point of the Procrustes mean shape (see Gunz
258 and Mitteroecker, 2013). This optimization aims to limit the effect of the former arbitrary spacing of
259 the points (Gunz and Mitteroecker, 2013; Perez et al., 2006), here equidistant. This optimization
260 and the superposition of the curves were carried out by Generalized Procrustean Analysis (GPA).
261 The new coordinates obtained by GPA were used to calculate a Principal Component Analysis
262 (PCA) and to visualize, with transformation grids (Klingenberg, 2013), the axes on which the shape
263 variations were the most important according to the manual preference. A Procrustes multivariate
264 analysis of variance (Procrustes ANOVA using the function “procD.lm” of package geomorph in R)

265 was used to test if the shape differences visualized according to the recorded factors (e.g. hand
266 holding the tool during use) were statistically significant. In other words, it allowed us to check if
267 specific scar distributions and specific used edge morphologies can be linked to the hand holding
268 the tool during use (i.e. left or right hand). The relationship between individuals' sex and the
269 resulting used edge shape was also tested.

270

271

Figure 3 (2 columns)

272

273 *k-Nearest Neighbours model*

274 In order to verify if the qualitative and quantitative descriptors of scars could be used to
275 discriminate a tool used with the right hand from a tool used with the left hand, we used the k
276 Nearest Neighbours (k-NN) machine learning algorithm. It was computed using the “caret” library
277 (Kuhn et al., 2019) in R. This algorithm uses Euclidean distances to find the k-Nearest Neighbours
278 of the artefact to be classified. The class which is the most frequent among the k Nearest
279 Neighbours is given to the unknown artefact (see Domínguez-Rodrigo and Baquedano, 2018 for
280 an example of application on cut-marks on bones). Twenty-one combinations of different
281 descriptors were tested:

282 1) Number of scars on the ventral and dorsal faces of the tool

283 2) types of scars on both faces

284 3) types of scars on dorsal face

285 4) types of scars on ventral face

286 5) directions of scars on both faces

287 6) directions of scars on dorsal face

288 7) directions of scars on ventral face

289 8) types and directions of scars on both faces

290 9) number, types and directions of scars on both faces

291 10) the 59 first principal components of the PCA on geometric morphometric data

292 11) the 2 first principal components of the PCA on geometric morphometric data

293 12) the 59 first principal components of the PCA on geometric morphometric data and the
294 number of scars on both faces

295 13) position of the scar with the maximum extent on the surface perpendicularly to the edge
296 on ventral face

297 14) position of the scar with the maximum extent on the surface perpendicularly to the edge
298 on dorsal face

299 15) position of the scar with the maximum extent on the surface perpendicularly to the edge
300 on both faces

301 16) maximum scar extent on the surface perpendicularly to the edge on ventral face

302 17) maximum scar extent on the surface perpendicularly to the edge on dorsal face

- 303 18) maximum scar extent on the surface perpendicularly to the edge on both faces
304 19) maximum scar extent and position of the scar with the maximum extent on the surface
305 perpendicularly to the edge on both faces
306 20) all descriptors from microscopic observation
307 21) all descriptors from microscopic observation and geometric morphometrics

308 We normalized the descriptors so their values were comprised between 0 and 1 to avoid
309 emphasizing descriptors with larger ranges of values. Each configuration was tested with each odd
310 number between 3 and 59 as k value (3 being the minimum odd number for such model and 59 the
311 maximum in our case as we had 60 artefacts). The k value of the final model was chosen based on
312 the obtained accuracy and kappa for each model. As our sample size (N = 60) is quite small, we
313 used leave-on-out cross-validation method to evaluate the models. In this method, the whole
314 sample set of analysed artefacts but one is used as a training set and the removed artefact is used
315 as a testing set. This procedure is repeated as many times as the number of artefacts in the
316 sample set. In addition, we used kappa statistics (value between -1 and 1 which measures the
317 agreement between observed and expected accuracy; negative values indicate disagreement, and
318 the degree of agreement increase from >0 to 1), sensitivity (a measure of the proportion of
319 attributed classes - i.e. positives - which are correctly attributed – i.e. true positives) and specificity
320 (a measure of the proportion of rejected classes – i.e. negatives - which are correctly rejected – i.e.
321 true negatives) to evaluate the performance of the selected model.

322

323

324 3. Results

325 3.1. Scars description

326 The scars qualitative description showed that independently of the hand holding the tool
327 during use: 1) tools have more extended scars on their dorsal face than on the ventral face, 2)
328 tools have mostly continuous scars on the dorsal face and discontinuous scars on the ventral face,
329 3) scars can be distributed all along the used edge and 4) scars are mostly perpendicular to the
330 edge. Therefore, no significant difference of position, type and orientation of scars between tools
331 used by left-handers and right-handers was noticed (Figure 4 and Supplementary figures 1 to 7).

332 However, right-handed subjects produced significantly more micro-scars than left-handed
333 subjects ($\bar{X} = 81.42$, $sd = 39.84$ for the tools used by right-handers versus $\bar{X} = 53.04$, $sd = 18.60$ for
334 the left-handers; Mann-Whitney U one-tailed test: $W = 240$, $p\text{-value} = 0.0011$). Micro-scars were
335 also significantly less invasive on tools used by left-handed subjects ($\bar{X} = 2.45$ mm, $sd = 1.13$ mm
336 for the tools used by right-handers versus $\bar{X} = 1.63$ mm, $sd = 0.73$ mm for the left-handers; Mann-
337 Whitney U one-tailed test: $W = 771$, $p\text{-value} < 0.0001$).

338 The hypothesis of independence between the hand holding the tool and the type of micro-
339 scars appearing on the surface of the tool could be rejected ($X^2 = 43.371$, $df = 4$, $p\text{-value} <$
340 0.0001). However, independence could not be rejected concerning the hand holding the tool and

341 the orientation of micro-scars ($X^2 = 0.66197$, $df = 2$, $p\text{-value} = 0.7182$) and the face where micro-
342 scars were located ($X^2 = 2.1323$, $df = 1$, $p\text{-value} = 0.1442$).

343

344 Among other chi-squared tests performed on this dataset we can notice that the type of
345 micro-scars is not independent from the sex of the user ($X^2 = 89.084$, $df = 4$, $p\text{-value} < 0.0001$) and
346 that the type of micro-scars, the orientation and the face where appeared micro-scars are not
347 independent from the user (respectively $X^2 = 587.75$, $df = 76$, $p\text{-value} < 0.0001$; $X^2 = 240.43$, $df =$
348 38 , $p\text{-value} < 0.0001$ and $X^2 = 114.05$, $df = 19$, $p\text{-value} < 0.0001$).

349

350

Figure 4 (2 columns) and Supplementary figures 1 to 7

351

352 3.2. Edge modification visualization and quantification through geometric morphometric

353

353 3.2.1. Comparison of edges before and after use

354

354 Before computing the geometric morphometric analysis, the extraction of each edge of
355 interest before and after use allowed comparing them to visualize the location of edge
356 modifications and the amount of removed material during use (Figure 5 and Supplementary figures
357 8 to 18. Most of the modification seem to be on the middle and the rear of the edge. Few tools
358 (40%, $N = 24/60$) present modifications on the front part of the edge but these modifications are
359 generally not invasive. No difference or clear tendency is noticed between tools used with left
360 versus the right hand regarding the amount of removed material and the location of modifications.

361

362

Figure 5 (1 column) and Supplementary figures 8 to 18

363

364 3.2.2. Used edges shapes quantification

365

365 The first two axes of the PCA on shape data account respectively for 23.26% and 11.79%
366 of the total variance (Figure 6). Groups of tools held with the right hand almost fully overlap with
367 the group of tools held with the left hand. Procrustes ANOVA confirmed that no pattern of shape of
368 used edge can be specifically attributed to tools used with the right hand versus tools used with the
369 left hand. (Procrustes ANOVA: $df = 1$, $SS = 0.0002$, $MS = 0.0002$, $Rsq = 0.0247$, $F = 1.4708$, $Z =$
370 1.4315 , $p\text{-value} = 0.101$). On the contrary, we noticed that the user and the sex of the user may
371 have a larger effect (than the hand holding the tool) on the shape of the used edges (Procrustes
372 ANOVA on shapes and users: $df = 19$, $SS = 0.0038$, $MS = 0.0002$, $Rsq = 0.4301$; $F = 1.5889$; $Z =$
373 4.5104 ; $p\text{-value} = 0.001$; Procrustes ANOVA on shapes and sex of users: $df = 1$, $SS = 0.0002$, MS
374 $= 0.0002$, $Rsq = 0.0324$; $F = 1.9407$; $Z = 2.3377$; $p\text{-value} = 0.029$).

375

376

Figure 6 (2 columns)

377

378 3.3. k Nearest Neighbours model

379 Among the 21 tested models, only five gave an accuracy of at least 75%, all are based on
380 descriptors concerning the maximum scar extent on the surface (perpendicularly to the edge). The
381 best model includes the maximum scar extent and the position of the scar with the maximum
382 extent on the surface (perpendicularly to the edge) on both faces. With a k value set up at 5, this
383 model provided an accuracy of 75% (95% confidence interval: 62%, 85%) with an acceptable
384 kappa of 0.51, a sensitivity of 85% and a specificity of 67% (Table 1).
385

386 **Table 1 (2 columns)**

387

388 4. Discussion

389 4.1. Can hand preference be identified from micro-scars?

390 We could not document any significant difference in position, type, and orientation of scars
391 between tools used by left-handers and right-handers. The microscopic observation showed that
392 tools have more extended scars on their dorsal face than on the ventral face regardless of which
393 hand the user preferred. Knowing that tools were always held with the same orientation during the
394 sawing action (with the dorsal face on the right) this result is counter intuitive. Indeed, during the
395 sawing action we usually observe a tilt of the tool toward the right for right-handers and towards the
396 left for left-handers usually resulting in more scars on the face placed on the left for right-handers
397 and on the right for left-handers. This result shows that hand preference has no influence on the
398 distribution of scars on either of the tool's faces. Combined with the fact that these tools had a
399 centred cutting edge, this result may show that the edge morphology and surface structure may
400 have an effect on the distribution of scars (when the glass casts were made, imperfections on the
401 edges were removed by polishing the ventral side of the edge only; this might have affected the
402 resilience of this face).

403 On the other hand, the type of micro-scars seems to be related to the hand holding the tool
404 during use. This is also a counter-intuitive result. However, as the tool had to be held in the same
405 orientation by left-handers and right-handers, the forces applied by left-handers, theoretically
406 symmetrical to those applied by right-handers, are applied on the opposite surface of the tool. As
407 mentioned above, the surface might have different resilience to contact during use and, as a
408 consequence, different types of micro-scars might have been produced. This should be tested in
409 future experiments. The suggestion that one of the surfaces (i.e. the dorsal face) of the tools might
410 be weaker than the other is somewhat supported by the fact that irrespective of which hand was
411 holding the tool, the dorsal face exhibited more scars.

412

413 Comparison of the edges before and after use did not show significant difference between
414 the amount of removed material and the location of modifications on tools used by left-handers and
415 right-handers. Right-handed subjects produced significantly more invasive and more numerous

416 micro-scars than left-handers but this is very likely to be due to an individual factor as, apart from
417 hand preference, the sex and the user seem to have a negligible effect on the characteristics of the
418 micro-scars. This was confirmed by geometric morphometric analyses which show that the shape
419 of the used edges depends more on the user and user's sex than on the hand preference.

420

421 Based on the data gathered through microscopic observation of scars and quantification of
422 edge modification with geometric morphometric, the k Nearest Neighbours method highlighted the
423 importance of the maximum scar extent (on the ventral face) and of the position of the more
424 invasive scar in discriminating hand preference during stone tool use. The model integrating these
425 variables gave 75% of good identification of the hand preference of the user.

426

427 4.2. Importance of individual characteristics

428 We decided not to choose experts at this step of the project because expertize in using
429 stone flakes (here more exactly soda lime-glass) is a complicated notion. How can we define an
430 expert user of stone flakes? Beginners are sometimes performing very well in such tasks. Like for
431 nowadays tools, a beginner might be more likely to damage the tool quicker than an expert might
432 but can we really consider someone as an expert stone flake user in the current world? Few have
433 more experience than others do and finding enough experienced people to produce statistically
434 acceptable data is not straightforward. In addition, experts may not have been the users of all the
435 archaeological pieces; expertise is not an information that we have archaeologically and we
436 intended to find parameters, which do not depend on the expertise to identify hand preference.

437 Thus, all of the individuals involved in this experiment were beginners in prehistoric tool
438 use. This lack of skill may be one of the reason why several scar features seem to be more related
439 to individual characteristics than to hand preference. The variability of grip and movements, even if
440 somehow constrained, likely influence scars production which may follow a pattern linked to the
441 way each individual used the tool. It can be supposed that in prehistory, frequent use of stones as
442 tools implies a certain degree of know-how and the transmission of this knowledge among
443 members of a particular community. A certain regularity in the way stone tools were used might be
444 expected. If so, individual characteristics might not exert such influence on scars features in
445 archaeological assemblages. However, in any discipline, experts often develop idiosyncratic
446 techniques which can be used to identify them. If stone tool use follows such a model, individual
447 characteristics may be very important in the process of scars formation and, for a specific
448 previously identified task, (even if unlikely because of the numerous variables possibly affecting
449 tool surfaces) it might be possible to evaluate the minimum number of different users within an
450 assemblage. This has to be tested in the future, involving experimenters skilled in stone tool use.

451

452 4.3. Hand holding the tool versus hand preference

453 The hand preference of an individual may vary depending on the action carried out
454 (Provins, 1997). For instance, in the frame of this experiment, one individual declared himself as
455 left-handed but spontaneously used the right hand to saw the wood during the whole experiment.
456 Also, some of the individuals asked to change the hand holding the tool (which was not allowed
457 here) because of pain due to this unusual task. In an unconstrained context (as in Prehistory), it is
458 likely that individuals would change hand if they feel pain or discomfort. Such modification of the
459 hand used during the tasks would highly complicate the identification of left-handed and right-
460 handed people based on archaeological stone tools. However, we can think that, during Prehistory,
461 stone tool use was a more frequent activity and pain and discomfort may have been less common.
462 In any case, such behaviours (as well as the case of ambidextrous people) demonstrate that what
463 we might intent to determine in an archaeological context is the hand holding the tool rather than
464 the hand preference of the user. Only the study of large samples through multi-proxy examination
465 might allow approaching hand preference.

466

467 4.4. Archaeological application

468 The results of this experiment, the k-NN results in particular, are promising and show that it
469 might be possible to identify the hand holding the tool during use based on micro-scars extent and
470 location. However, even if 75% of correct identification is acceptable, it remains valid for a
471 constrained experimental context in wood sawing activity only. We can expect a drastic drop of
472 accuracy in unconstrained situations. Indeed, it is for instance essential to consider that one tool
473 could have been used several times, for various activities, and by different users. Furthermore, in
474 an archaeological assemblage, it is very unlikely to deal only with artefacts used in sawing wood
475 activities. It is now essential to extend the experimental reference corpus with unstandardized
476 pieces (used for different activities), to improve the model with other traces (residues, micro-
477 polishes, striations), and to validate the results with blind-tests before any application on
478 archaeological assemblages. Such an application could be considered when a strong enough (i.e.
479 more than 90% accuracy) experimental model will be ready. It requires a large experimental
480 collection on which each of the traces will be examined and documented. Our model involves
481 parameters that are not dependent on the population ratio of right and lefthanders and is only
482 based on repeatable measurements and description. Once improved, we will be able to propose a
483 new proxy which could provide different result concerning hand preference ratio in Prehistory or
484 reinforce the obtained results from the other disciplines.

485

486 5. Conclusion

487 Wear analysis, geometric morphometric and machine learning provided complementary
488 results in order to examine if the hand holding the tool during use could be identified based on
489 micro-scars. However, the k-NN method showed that the data provided by geometric
490 morphometric and numerous data coming from wear analysis do not help in improving the

491 accuracy of the model of classification. Nevertheless, counter-intuitive results may indicate a bias
492 related to the structure of the tool used in this experiment and these non-significant variables from
493 geometric morphometric and wear analysis should not be rejected definitively before further
494 experiments. Moreover, the heterogeneity of raw materials used in prehistoric times may lead to
495 similar results. The best model (75% accuracy) is obtained when based on the maximum scar
496 extent and the position of the scar with the maximum extent on the surface of the tool
497 perpendicularly to the edge on both faces. Other variables show overlap for tools used with the left
498 hand and tools used with the right hand, and are likely to depend rather on individual
499 characteristics.

500 This first experiment, with standardized tools dedicated to hand preference identification,
501 yielded promising results and already highlighted variables that could be used as discriminants.
502 Nevertheless, the experimental corpus needs to be extended and the model tested further to
503 provide reliable results from archaeological assemblages.

504

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524

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Fig.1: Soda-lime glass replica used in the experiment.

Fig.2: Documentation of the type, orientation and position of maximum extent of the micro-scars.

Fig.3: Used edges curves extraction for geometric morphometric analysis. A) Example of photograph taken after use. B) Binarization. C) Scaling of outlines. D) The line going through the extremities of each outline is placed horizontally, the outlines are then wedged on the rightmost point. E) The average coordinates of the uppermost points of the outlines is calculated and the uppermost point of each outline is aligned on it. F) The edge of interest is extracted by cutting the outline at the uppermost point and at the leftmost point.

Fig.4: Examples of position and orientation of micro-scars for left and right-handers.

Fig.5: Comparison of tool edges before and after use for left and right-handers.

Fig.6: Two first axes of the principal component analysis of the coordinates obtained by Generalized Procrustean Analysis (GPA) of the curves representing the used edges of the tools used by left-handers and right-handers. The used edge shape reconstructions are displayed for the minimum and the maximum values of each PC.

Table 1: Results of the k Nearest Neighbours models. Models providing the best accuracy are in bold.

1cm



A)



Break



Feathered



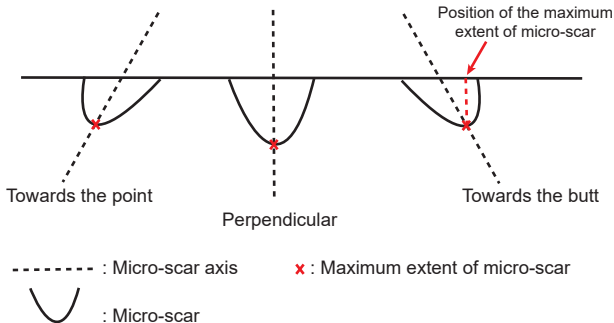
Step



Abrupt

After Vaughan (1985)

B)



Position of the maximum extent of micro-scar

Towards the point

Perpendicular

Towards the butt

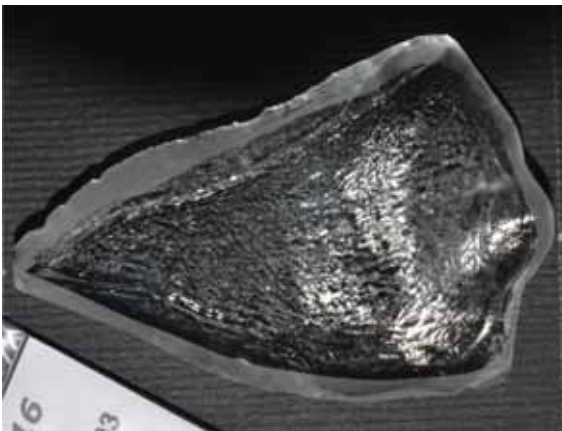
----- : Micro-scar axis

x : Maximum extent of micro-scar

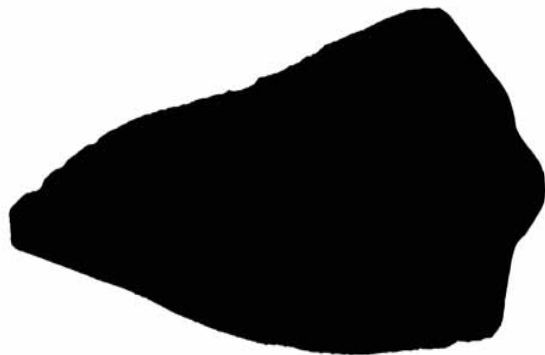


: Micro-scar

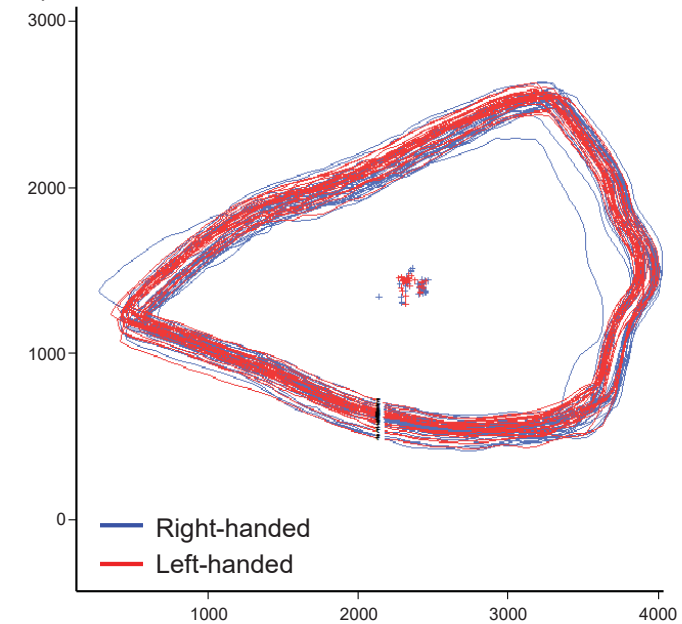
A)



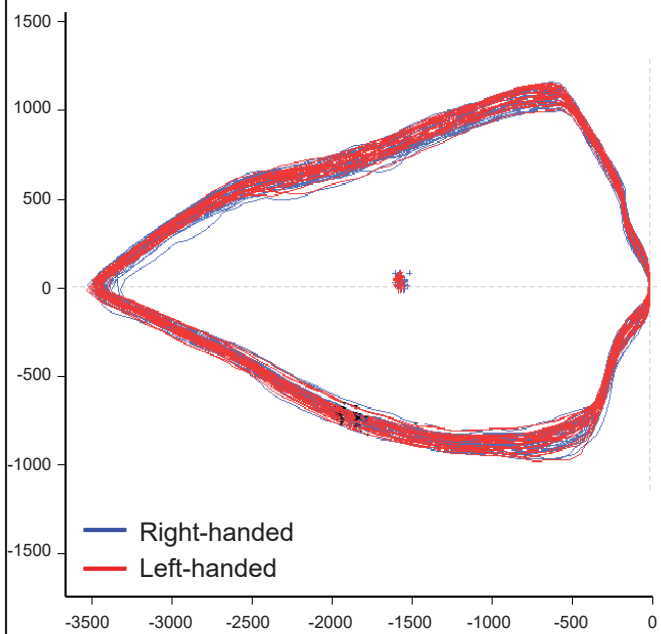
B)



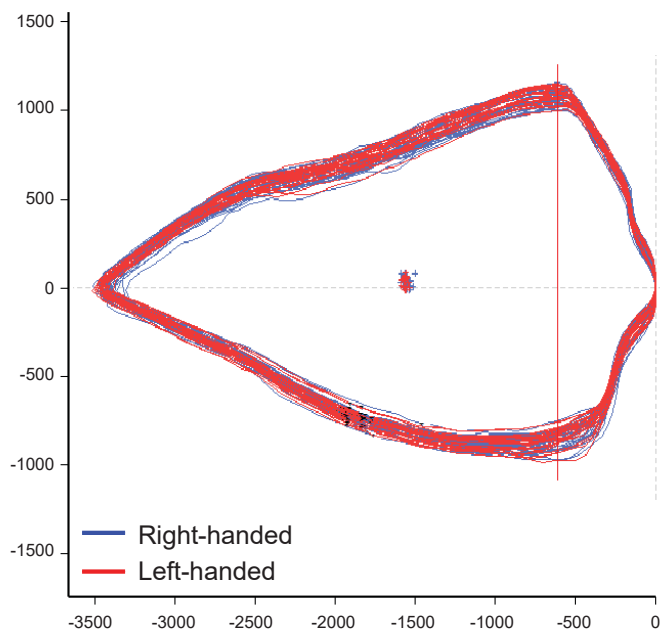
C)



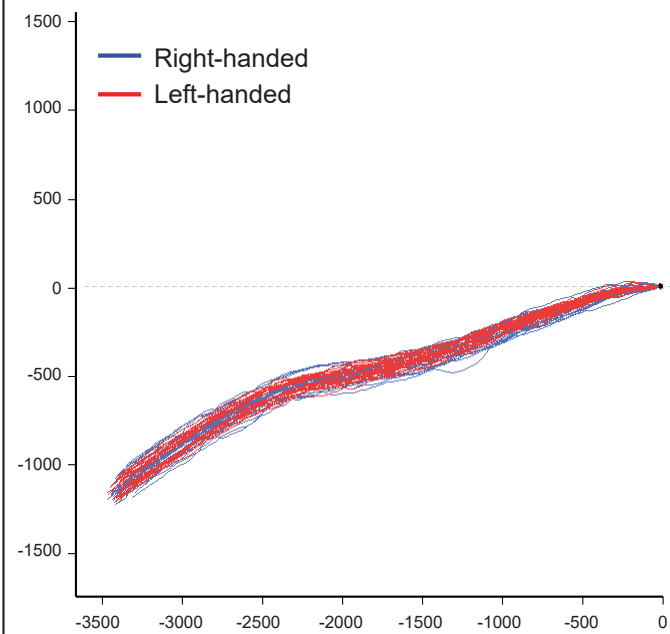
D)



E)

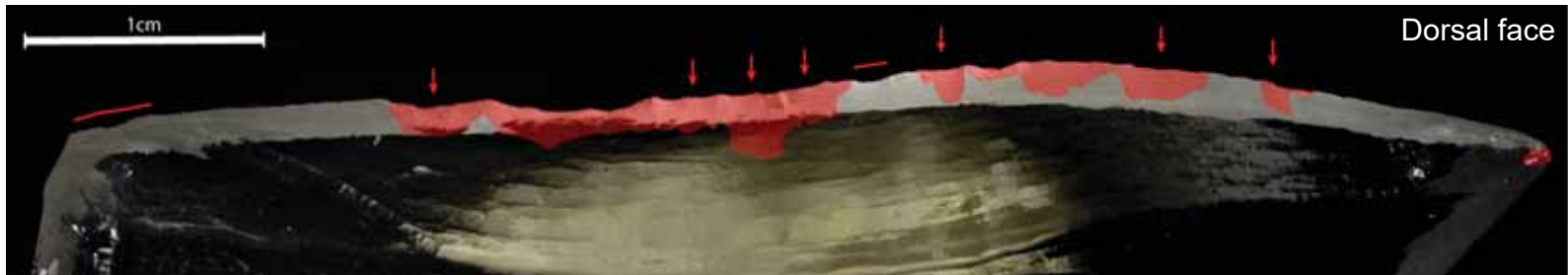
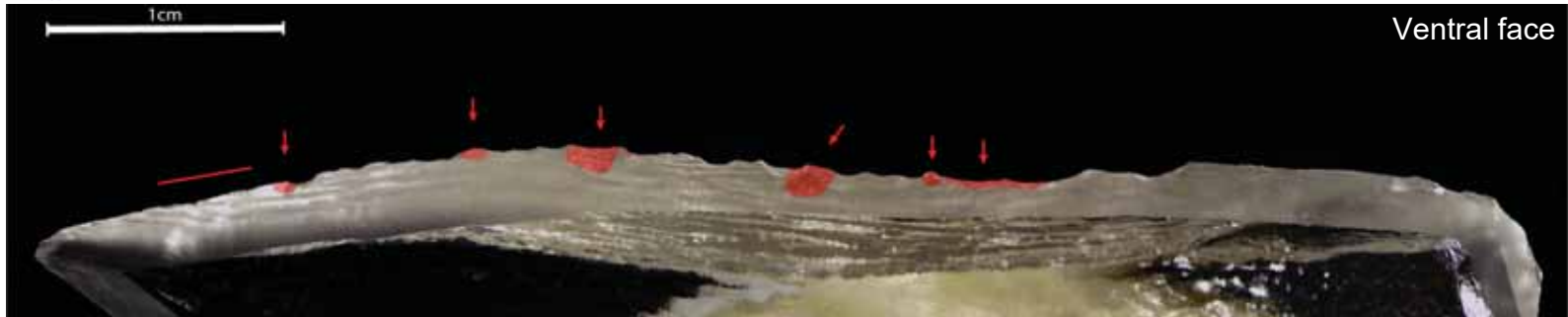


F)

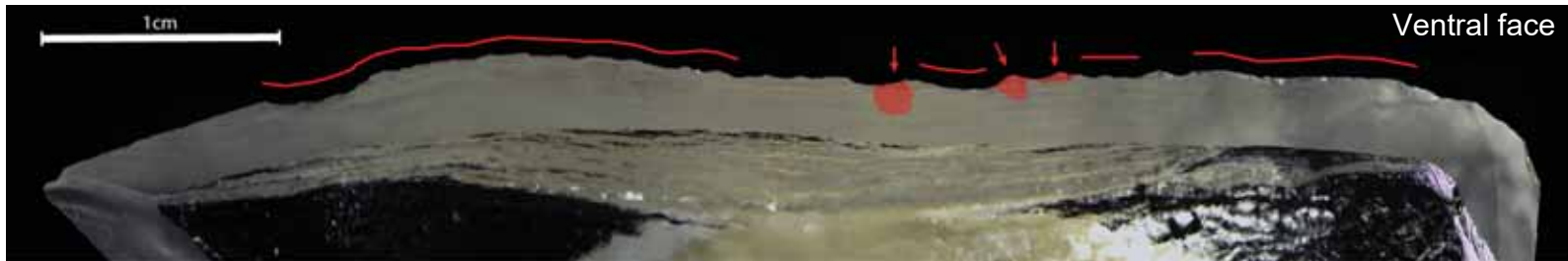




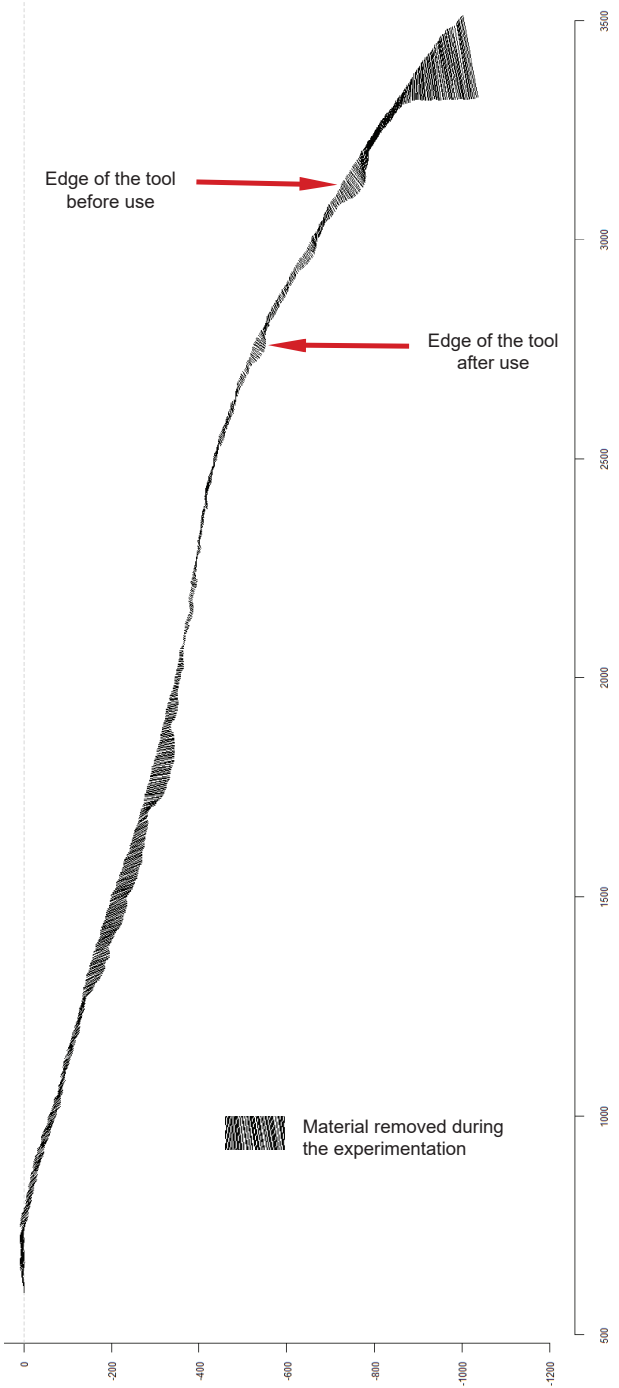
Tool used by a left-hander



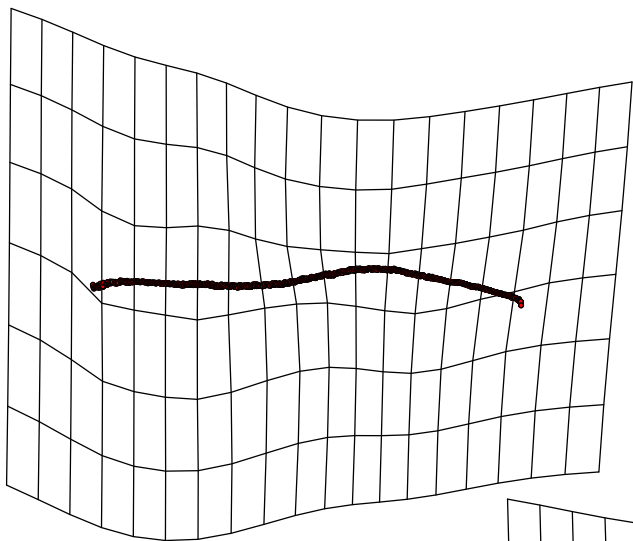
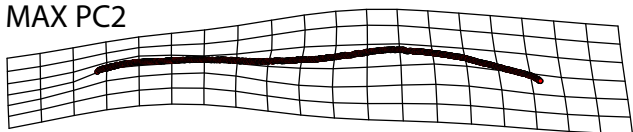
Tool used by a right-hander



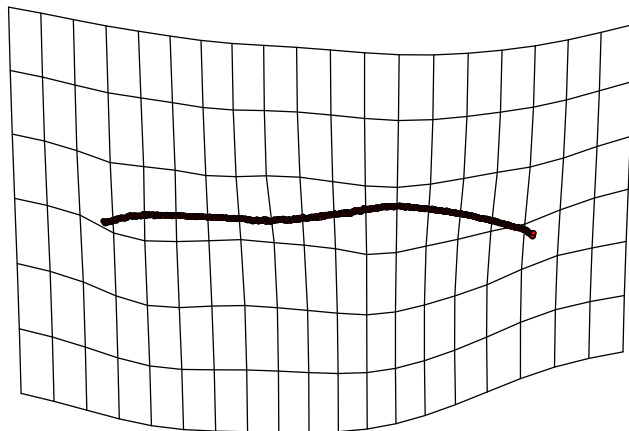
↓ : General orientation of the micro-scars ■ : Micro-scars extent — : Edge modification visible at a magnification higher than 10X



MAX PC2



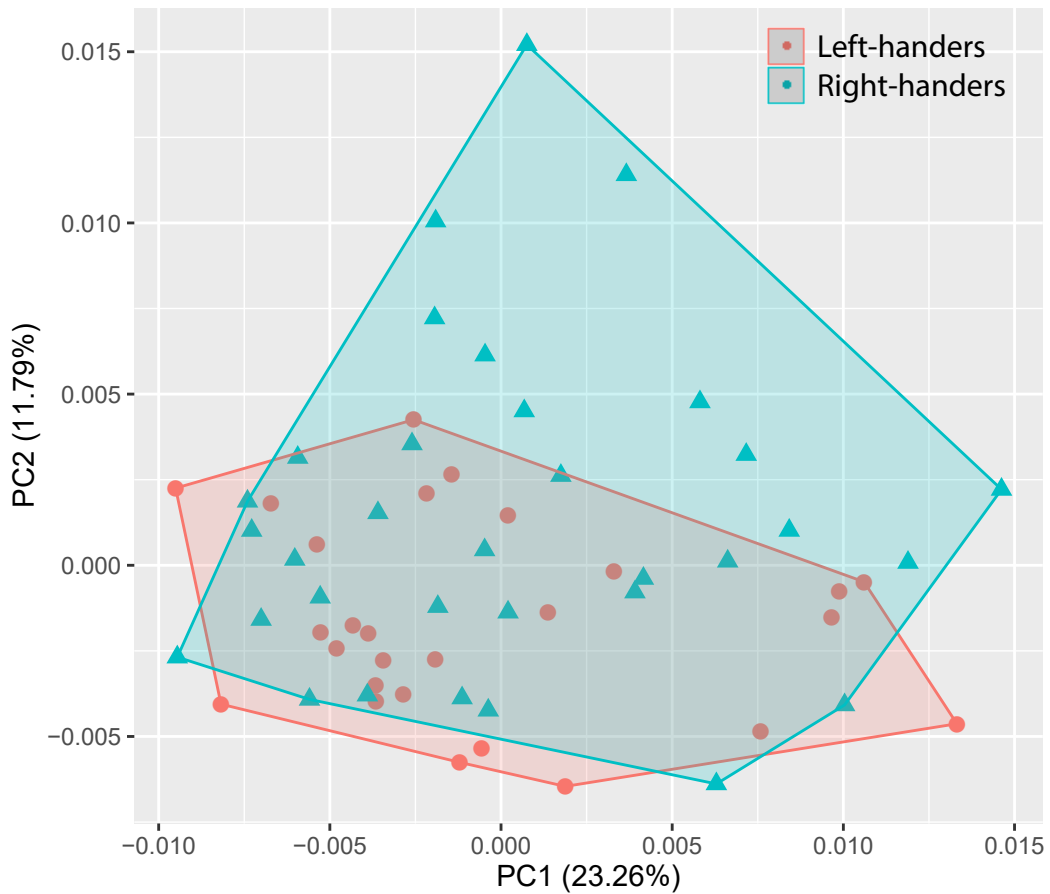
MIN PC2



MIN PC1



MAX PC1



Model n°	Included variables	K-value giving best results	Accuracy	95%CI	Kappa	Sensitivity	Specificity
1	Number of scars on the ventral and dorsal faces of the tool	23	0.65	0.5160, 0.7687	0.3092	0.7407	0.5758
2	Types of scars on both faces	9 & 11	0.6833	0.5504, 0.7974	0.3537	0.5926	0.7576
3	Types of scars on dorsal face	5	0.7	0.5679, 0.8115	0.398	0.7037	0.6970
4	Types of scars on ventral face	31	0.6	0.4654, 0.7244	0.1864	0.5185	0.6667
5	Directions of scars on both faces	17 & 27	0.6	0.4654, 0.7244	0.2131	0.7037	0.5152
6	Directions of scars on dorsal face	41	0.6333	0.499, 0.7541	0.2834	0.7778	0.5152
7	Directions of scars on ventral face	21	0.6333	0.499, 0.7541	0.2691	0.6667	0.6061
8	Types and directions of scars on both faces	25	0.65	0.516, 0.7687	0.3	0.6667	0.6364
9	Number, types and directions of scars on both faces	27	0.6167	0.4821, 0.7393	0.2333	0.6296	0.6061
10	The 59 first principal components of the PCA on geometric morphometrics data	55 & 57 & 59	0.55	0.4161, 0.6788	0	0	1
11	The 2 first principal components of the PCA on geometric morphometrics data	31	0.5833	0.4488, 0.7093	0.1776	0.6667	0.5152
12	The 59 first principal components of the PCA on geometric morphometrics data and the number of scars on both faces	13 & 15	0.65	0.516, 0.7687	0.3	0.6667	0.6364
13	Position of the scar with the maximum extent on the surface perpendicularly to the edge on ventral face	17 & 47	0.7333	0.6034, 0.8393	0.4539	0.6296	0.8182
14	Position of the scar with the maximum extent on the surface perpendicularly to the edge on dorsal face	21 & 23	0.5833	0.4488, 0.7093	0.1611	0.5556	0.6061
15	Position of the scar with the maximum extent on the surface perpendicularly to the edge on both faces	11	0.7333	0.6034, 0.8393	0.4613	0.7037	0.7576
16	Maximum scar extent on the surface perpendicularly to the edge on ventral face	25 & 37	0.75	0.6214, 0.8528	0.4966	0.7407	0.7576
17	Maximum scar extent on the surface perpendicularly to the edge on dorsal face	21 & 23	0.7333	0.6034, 0.8393	0.4613	0.7037	0.7576
18	Maximum scar extent on the surface perpendicularly to the edge on both faces	23	0.75	0.6214, 0.8528	0.5	0.7778	0.7273
19	Maximum scar extent and position of the scar with the maximum extent on the surface perpendicularly to the edge on both faces	5	0.75	0.6214, 0.8528	0.5066	0.8519	0.6667
20	All descriptors from microscopic observation	5	0.75	0.6214, 0.8528	0.5	0.7778	0.7273
21	All descriptors from microscopic observation and geometric morphometrics	9	0.75	0.6214, 0.8528	0.5066	0.8519	0.6667