

# Geometric morphometrics for provenance determination of Gallo-Roman white clay figurines

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## Abstract

*Hundreds of Gallo-Roman white clay figurines coming from the center of France and available in the French museums have been digitized by the Centre de Recherche et de Restauration des Musées de France using three-dimensional surface scanner technologies. Shapes of the statuettes differ according to many parameters, they may vary according to the sites of origin, the author of the works and they might reflect local influences of the workshops from which they originate.*

*In this paper, we describe methods used to quantify and compare the shapes of the figurines and interpret results obtained by using such methods on a set of three-dimensional virtual objects. We show the results of these methods applied to a set of three dimensional virtual objects based on homologous points (landmarks) systematically defined and placed on the virtual models of mother goddess and Venus figurines. We use geometric morphometrics, including essentially generalized Procrustes analysis, to measure and display the differences in shapes and characterize the provenance of the Gallo-Roman figurines. Various analyses including chemical methods have been already carried out to determine the provenance of the statuettes and provide a basis for the comparison of our results.*

*According to the results of the statistical analysis we assess the advantages and limitations of geometric morphometrics for the characterization of the provenance of the white clay figurines. Finally, from a broader perspective, we comment the interpretation of morphometrical analyses applied to archaeological objects.*

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Geometric algorithms, languages, and systems

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## 1. Introduction

Dating from the beginning of the Christian era, terracotta statuettes appear in the archaeological remains of the Gallo-Roman settlements of the Allier and Loire valleys in France. These figurines were made of white clay and had a decorative as well as a religious role. They represent various gods and animals, but the main subjects are two types of goddesses, Venus and Mother Goddesses.

Archaeological studies [BJL93] reveal that these figurines were produced in definite workshops by a reduced number of artists. Although the location of discovery of the statuettes is usually a good indicator of the workshop of origin, evidences such as chemical composition [RL91] or signatures of known artists found on the figurines reveal that some of

the statuettes have been found far from their place of production probably because used for the cultural and economical exchanges between Gallo-Roman settlements.

All figurines differ by stylistic changes in the representation of their faces, clothes and hairstyles. The EROS (European Open Research System [LAP03]) database of the Centre de Recherche et de Restauration des Musées de France contains hundreds of three-dimensional models of Gallo-Roman statuettes. They have been digitized using a laser scanner with a resolution of about 50  $\mu\text{m}$  which allows to proceed to precise measurements and further geometric analyses.

We use three-dimensional scans of Mother Goddesses and Venus to perform a morphometric analysis of the statuettes, in order to determinate a correlation between the variability of the shape of figurines and the origin of the figurines.



**Figure 1:** Virtual models of two Mother Goddesses and a Venus. The second and the third are moulds.

In the next section, we describe the choice for the placement of homologous points on the faces of the statuettes to account for the shape of the objects. Sets of points are used to perform a generalized Procrustes analysis, whose outputs serve for a principal component analysis. The visualization of principal components of the figurines outlines the relationship between the shape of the figurines and their locations of origin.



**Figure 2:** Main sites of provenance of Gallo-Roman white clay figurines

## 2. Materials

### 2.1. Figurines

The set of objects of interest consists in 29 figurines from the collections of French Museums. All studied statuettes are Goddess Mothers or Venus. The details of the objects are given in table 1. Some of the objects are actually moulds, which were sometimes used to copy figurines or to assort different front and back parts of two models. As we only

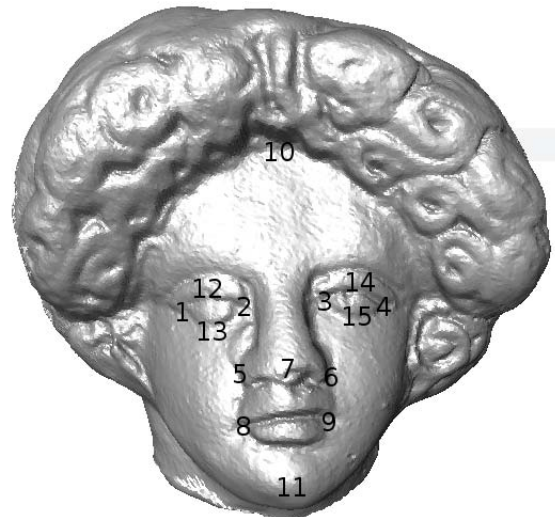
Location of origin	Number of figurines
Alise-Sainte-Reine	3
Laignes	1
Saint-Pourçain-sur-Besbre	2
Toulon-sur-Allier	19
Vichy	4

**Table 1:** Figurines used in our morphometric analysis

take into account the front parts of the statuettes, this technique has no influence on our study. Moulds also explain why some statuettes are identical.

For further interpretation of our results, it is pertinent to note that the locations of origins of the statuettes can be separated in 3 groups of close locations:

1. Alise-Sainte-Reine and Laignes
2. Saint-Pourçain-sur-Besbre and Toulon-sur-Allier
3. Vichy



**Figure 3:** Position of landmarks on a Venus head

### 2.2. Data acquisition

The three-dimensional models were acquired using a Minolta Vivid 900 laser scanner [Kon] which captures data from several points of view. The partial models go through an alignment and a post-processing steps to provide a single virtual model of the figurine with an accuracy of tenths of microns. Laser scanner fits particularly the needs of archaeological and museological data digitization, as it works without contact. Moreover, the white clay of the statuettes limits the possible problems linked to scanning optical devices as it shows limited reflectivity.

We have used a laser scanner to get our three-dimensional virtual data, but any other 3D surface scanner technique can be used, including structured light scanning or photogrammetry. In the specific case of white clay statuettes, laser scanners and structured light scanners are particularly adapted because of the relative high resolution of these techniques which is necessary to place accurate landmarks.

### 3. Methods

Taking inspiration from many studies carried out in the field of anthropology [RCL92], [SLi05], we apply a classical morphometric protocol for the analysis of shapes. It consists in placing homologous points on the virtual objects, then applying a generalized Procrustes analysis on the sets of landmarks and finally projecting the aligned coordinates on principal axes [ARS04].

Software used for the further analysis are already available (see below) and no particular code was written for this application.

#### 3.1. Landmarks

To quantify the variability of shapes, we need to define homologous points on each statuette. These landmarks are chosen to provide reproducible reference points corresponding to one of the three types of landmarks defined by Bookstein [Boo91]:

- Type I: discrete juxtaposition of tissues
- Type II: maxima of curvature or other local morphogenetic processes
- Type III: extremal points

In the case of moulds, mirroring the landmarks is sufficient to compensate the negative geometry of the objects, e.g. landmark # 1 becomes landmark # 4.

The landmarks are placed manually using Amira [Ami], a proprietary software. Complete point sets are available for each statue.

#### 3.2. Generalized Procrustes analysis

Generalized Procrustes analysis [Gow75], [Goo91], [DM98], is a method for the comparison of sets of landmark configurations. Coordinates of landmarks set to characterize the shape of statuettes vary according to location and orientation of each object in the coordinates system of the digitizing device space. Generalized Procrustes analysis (GPA) solves this issue in scaling, rotating and translating each object to minimize the sum of squared distances between homologous landmarks on each configuration and a mean configuration, which is iteratively computed.

From a practical point of view, each time a mould was put in an oven, it used to lose 8 % to 10 % of its volume because of water evaporation. Apart from the changes in size due to the artistic choices, this phenomenon also explains why we

#	Landmark	Type
1	External corner of right eye	I
2	Internal corner of right eye	I
3	Internal corner of left eye	I
4	External corner of left eye	I
5	Right corner of the nose	III
6	Left corner of the nose	I
7	Most advanced point on the nose	III
8	Right corner of the mouth	I
9	Left corner of the mouth	I
10	Middle of hairline	I
11	Most advanced point of the chin	III
12	Upper point on the right eye line	III
13	Lower point on the right eye line	III
14	Upper point on the left eye line	III
15	Lower point on the left eye line	III

**Table 2:** List of landmarks used to describe the shape of figurine faces

use scale-invariant methods for the analysis of the statuettes. We consider  $n$  configurations matrices  $X_1, \dots, X_n$ , i.e. matrices of  $k = 15$  landmarks in  $m = 3$  dimensions.

1. *Translation.* Each configuration is centered to remove location, by calculating the centroid of each shape and translating it to the origin.

$$X_i^t = X_i - \frac{1}{k} \sum_{j=1}^k X_j \quad (1)$$

2. *Scaling.* The configuration  $X_i^t$  is scaled to the Centroid Size, which is the square root of the sum of squared distances of a set of landmarks from their centroid.

$$CS = \left( \sum_{j=1}^k \left( \|X_{i(j)} - \frac{1}{k} \sum_{j=1}^k X_{i(k)}\| \right) \right)^{1/2} \quad (2)$$

where  $X_{i(k)} = (X_{i(k1)}, X_{i(k2)}, X_{i(k3)})^T$  is the coordinate vector for the  $k^{th}$  landmark.

$$X_i^s = \frac{X_i^t}{CS} \quad (3)$$

3. *Rotation.* For each configuration  $i$ , minimize the difference between the mean matrix and the configuration matrix. The mean matrix  $\bar{X}$  is the mean of all configuration matrices.

$$X_i^r = \min(\|X_i^s - \bar{X}\|) \quad (4)$$

After these 3 steps, a new mean configuration is calculated and the process is iterated until the mean configuration is stable.

This process brings all landmark configurations to the same coordinate system in which the variations of coordinates of the landmarks expresses the variability of shapes.

### 3.3. Statistics

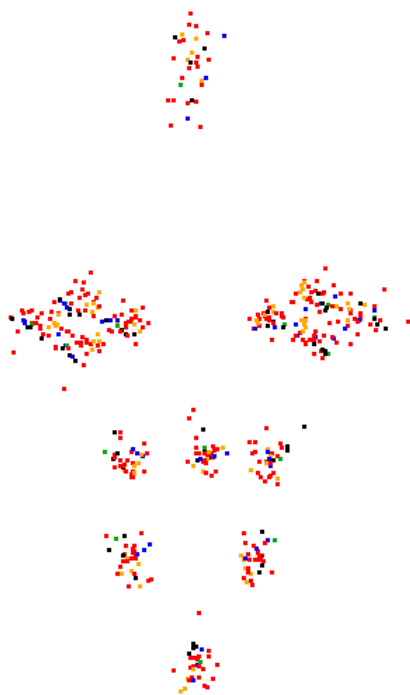
High dimensionality (45 dimensions) of the shape vectors resulting of the GPA, makes the interpretation of shape variability complicated without any further treatment. To address this issue, the morphometrical workflow usually has recourse to principal component analysis (PCA) to reduce the set of values accounting for the shape variability. PCA allows to provide a basis for the visualization of the covariation among the shape variables and is the last step before the interpretation of data.

All morphometric and statistical methods have been applied using the EVAN toolkit [Et], an open-source software.

## 4. Results

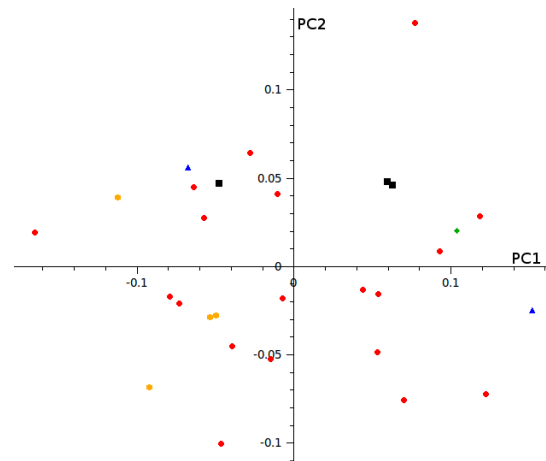
### 4.1. Shape space

The superimposition of the 29 landmark configurations (see figure 4) reveals that the shape of the faces of some groups of statuettes seems especially homogenous. In particular, the statuettes coming from Vichy form a separate group which seems to have its own morphometric specificities. For the other groups of statuettes, a first analysis is more difficult, but the PCA allows to extract more information from the sets of landmarks. PCA reveals that the first and second princi-



**Figure 4:** Superimposition of the 29 landmark configurations after the GPA. Red: Toulon-sur-Allier, black: Alise-Sainte-Reine, blue: Saint-Pourçain-sur-Besbre, orange: Vichy, green: Laignes.

pal components account for 99.3 % of the total variance. The repartition of the specimens along these two principal axes (see figure 5) shows that the statuettes coming from Vichy are characterized by a negative score on PC1, while the ones coming from Alise-Sainte-Reine or Laignes are characterized by a positive score along PC2.



**Figure 5:** First and second PC scores for the set of statuettes. Red: Toulon-sur-Allier, black: Alise-Sainte-Reine, blue: Saint-Pourçain-sur-Besbre, orange: Vichy, green: Laignes.

### 4.2. Shape variability

The GPA and PCA process allows to visualize the main axes of shape variation. PCA allows to reduce the dimensionality of the problem and to decompose variability into orthogonal components. Each successive principal component explains the remaining highest variability in the data. In the case of independent and isotropic points (i.e. random shapes) the eigenvalues are approximately equal. On the contrary, in the case of a strong dependency between landmarks, the largest amount of the variability would be carried by the first principal components.

A positive variation of landmark configuration along PC1 corresponds particularly to distant and large eyes, a large nose and a high mouth, while a positive variation along PC2 is connected to a high nose, a low chin and horizontal eyes. Warpings of landmark configurations along PC1 and PC2 are shown on figures 6 and 7.

### 4.3. Localization determination based on shape classification

Figure 8 presents the typical shapes for some origins of statuettes. It is noticeable that Vichy statuettes are characterized by a narrow face and a low mouth, corresponding to a negative displacement along PC1, while the figurines coming

from Alise-Sainte-Reine are recognizable by their large nose and low chin, typical of a positive displacement along PC2. The unique figurine from Laignes has also a shape close from the ones of Alise-Sainte-Reine.

Nevertheless, the set figurines of Toulon-sur-Allier is scattered in the shape space and shows the limitations of interpretation of the shape analysis based only on the faces of the statuettes.

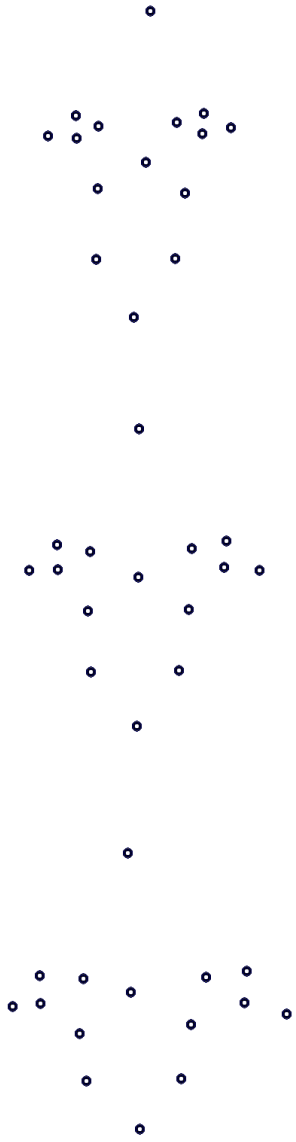
## 5. Conclusions

Geometric morphometrics provide tools to help to characterize the location of production of Gallo-Roman white clay figurines. Generalized Procrustes analysis allows to separate groups of figurines according to their spatial provenance and shows that shape analysis based on three-dimensional surface digitized models gives a complementary method to chemical analyses for the location determination of archaeological objects. However, the interpretation of the results is limited by the size of our sample of study and would be improved by the use of a larger pool of three-dimensional virtual models.

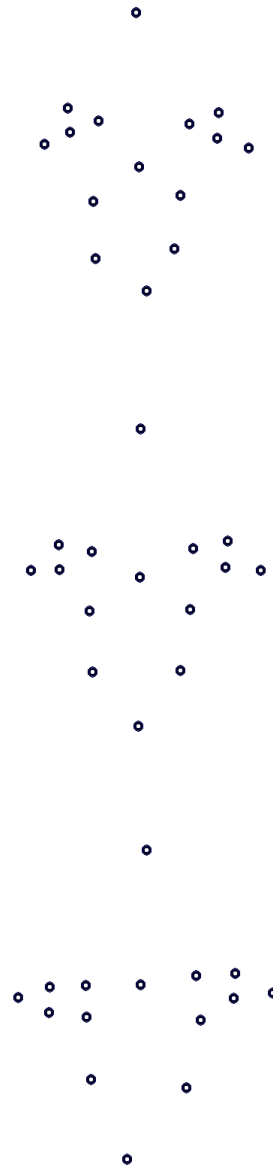
Morphometric analysis seems not to be sufficient to segregate figurines by clusters according to their geographic origin. Gorisse et al. [GCJ\*09], using three-dimensional features as Extended Gaussian Images or 3D Hough transform, show that autolearning methods can only classify 80 % of the models correctly. From the same perspective, morphometrics methods can give indications for the classification of the statuettes, as other numerical methods can. Finally a method for pure automatic classification is not yet available and only human archaeological expertise can assure that a semi-automatic classification system manages to achieve the classification of complex elements.

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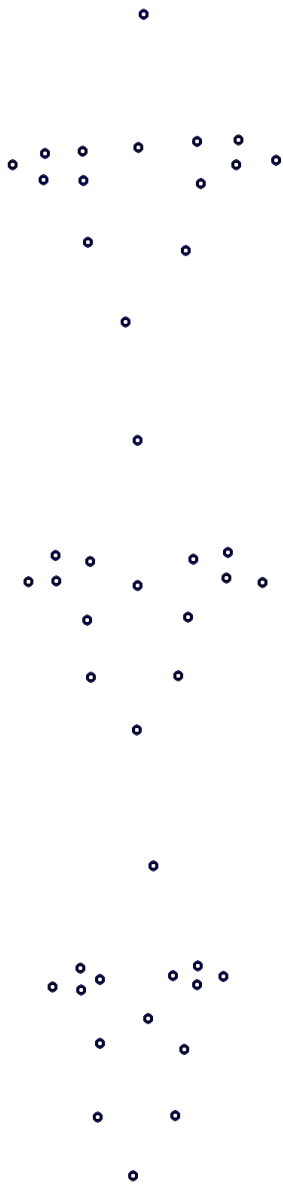
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**Figure 6:** Variation of configuration along PC1. Up: PC1 = -0.2, center: mean configuration, down: PC1 = 0.2



**Figure 7:** Variation of configuration along PC2. Up: PC2 = -0.2, center: mean configuration, down: PC2 = 0.2



**Figure 8:** Mean configuration for several origins of statuettes. The deformation is exaggerated 5 times to help visualize the shape differences. Up: Alise-Sainte-Reine, center: Toulon-sur-Allier, down: Vichy