Int J Legal Med (2009) 123:333–344
DOI 10.1007/s00414-009-0339-6

CASE REPORT

Geometric morphometric methods for three-dimensional virtual reconstruction of a fragmented cranium: the case of Angelo Poliziano

S. Benazzi · E. Stansfield · C. Milani · G. Gruppioni

Received: 24 October 2008 / Accepted: 3 March 2009 / Published online: 18 March 2009

Abstract The process of forensic identification of missing individuals is frequently reliant on the superimposition of cranial remains onto an individual's picture and/or facial reconstruction. In the latter, the integrity of the skull or a cranium is an important factor in successful identification. Here, we recommend the usage of computerized virtual reconstruction and geometric morphometrics for the purposes of individual reconstruction and identification in forensics. We apply these methods to reconstruct a complete cranium from facial remains that allegedly belong to the famous Italian humanist of the fifteenth century, Angelo Poliziano (1454–1494). Raw data was obtained by computed tomography scans of the Poliziano face and a complete reference skull of a 37-year-old Italian male. Given that the amount of distortion of the facial remains is unknown, two reconstructions are proposed: The first calculates the average shape between the original and its reflection, and the second discards the less preserved left side of the cranium under the assumption that there is no deformation on the right. Both reconstructions perform well in the superimposition with the original preserved facial surface in a virtual environment. The reconstruction by means of averaging between the original and reflection yielded better results during the superimposition with portraits of Poliziano. We argue that the combination of computerized virtual reconstruction and geometric morphometric methods offers a number of advantages over traditional plastic reconstruction, among which are speed, reproducibility, easiness of manipulation when superimposing with pictures in virtual environment, and assumptions control.

Keywords Virtual anthropology · Cranium reconstruction · Geometric morphometrics · Superimposition techniques

Introduction

Reconstruction of facial and neurocranial morphology has played an important role in forensic anthropology, paleoanthropology, and medical science. In forensic anthropology, skeletal remains are often the only retrieved parts of missing individuals. As a result, various physical anthropological techniques have been developed to identify a victim from skeletal remains [1]. In this context, cranial remains are frequently used not only in the assessment of an individual's sex and age [2] but also in dental [3] and skull–photo superimposition for the purpose of their personal identification [4–8]. Moreover, plastic craniofacial reconstruction can be performed only on the entire skull of the individual. The plastic reconstruction creates an approximation of the individual's face at the time of death that sufficiently resembles the deceased person to allow recognition [9–11]. This is true not only for facial reconstruction based on

S. Benazzi and E. Stansfield contributed equally to this work.

S. Benazzi (✉) · E. Stansfield
Department of Palaeoanthropology and Messel Research,
Senckenberg Research Institute,
Senckenberganlage 25,
60325 Frankfurt am Main, Germany
e-mail: sbenazzi@senckenberg.de

C. Milani
Department of Genetics, Evolution and Anthropology,
University of Parma,
Parco Area delle Scienze 11/A,
43100 Parma, Italy

G. Gruppioni
Department of History and Methods for the Conservation of Cultural Heritage, University of Bologna,
Vicolo degli Ariani 1,
48100 Ravenna, Italy

manual methods in which modeling clay or plasticine are applied on a cast of the skull [12, 13] but also for computer-based forensic facial reconstruction [14, 15].

It is obvious that the precision of a reconstruction depends on the completeness of the skull. In other words, the more parts that are missing on the skull, the less reliable the skull–photo superimposition becomes, therefore resulting in an inadequate facial reconstruction. In order to overcome this limitation, recreating the complete skull is often required. Nowadays, there are two different approaches recognized: a “traditional” and a “virtual” one. In the former approach, the reconstruction is carried out by a specialist directly on the bone so that a physical contact with the bone is required. The replacement of missing parts involves reproducing the external integrity of the bony segment by means of dental wax or hot paste made of organic and inorganic components (modeling chalk, raw beeswax, rosin, zinc white). This reconstruction method is highly subjective, and accuracy of the result decreases as the size and complexity of the bony parts under reconstruction increase. The second approach to reconstruction, i.e., virtual techniques such as reverse engineering and geometric morphometrics, has been shown to minimize the effect of the subjective choices of the operator and increase the reliability of the result [16–20].

Three-dimensional virtual reconstructions have recently been used for planning mandibular reconstruction [21], modeling of the orbital cavity [22], and in maxillo-facial surgery [23, 24]. They are also widely used in paleoanthropological research [25–28], which illuminates the great potential of the new three-dimensional technologies. The problems faced in paleoanthropology are very similar to those found in forensic anthropology because fossil skulls are often heavily distorted and fragmented. Consequently, the methods developed in paleoanthropology in order to solve the problem of deformation [29] and reconstruction of missing data [18, 27] can be rightfully applied in forensic anthropology for reconstruction of fragmented skulls for identification purposes.

In this study, we applied a computerized method of reconstructing missing cranial data to the case of a famous fifteenth century Italian humanist, Angelo Poliziano. An entire skull was reconstructed using virtual models and geometric morphometric methods (GMM) starting with a preserved portion of the face. We attempted to use the most reliable methods available, always aware that it is impossible to reproduce the morphology with absolute precision. Moreover, since the Italian humanist had been depicted in numerous paintings, the reconstructed skull will be virtually superimposed onto the paintings of a middle-aged Poliziano in order to verify his identity.

There is a protocol for the skull/painting superimposition that has been proposed and developed in the past [30, 31]. It requires establishing consensus between paintings and, when available, verbal descriptions of the historic character. The challenge, in our case, was that there was little resemblance among several known portraits of Angelo Poliziano. Moreover, it is well known that portraits dated by fifteenth to sixteenth centuries frequently lacked precision and technique characteristic of the later ages. As a result, any attempt of Poliziano's identification would be only as reliable as the painting chosen for superimposition. Nevertheless, we use this opportunity to present the virtual methods of facial reconstruction and superimposition in forensics.

Anthropological recognition

In July 2007, the graves of two important fifteenth century Italian humanists were opened in order to shed light on their sudden deaths that were historically recorded. Angelo Poliziano (1454–1494) and his friend, the humanist Giovanni Pico della Mirandola (1463–1494), died within a short period of time in Florence under mysterious circumstances. They were subsequently buried into two different graves in the S. Marco cloister (Florence). Poliziano's skeleton remains were preserved worse than those of Giovanni Pico, probably due to the more humid condition of the place in which he was buried.

One of the problems faced by anthropologists was the correct identification of the two individuals in relation to the description reported in the historical sources [32–35].

The well-preserved skeletal remains of a tall and robust male were consistent with descriptions of Pico as reported in the historical sources [34]. In contrast, the presumed cranial and post-cranial bones of Poliziano were fragmented and extremely fragile to the extent that the traditional physical anthropological techniques that were applied for identification of Poliziano remains have not yielded an assertive result. Furthermore, given the bad preservation of the bones and the lack of living relatives, DNA could not provide any aid for his identification. No useful verbal descriptions of the facial features of Angelo Poliziano were available, but there were a number of paintings that were made during his life or shortly after his death. As a result, it has been suggested that superimposition of the remains with the paintings should comprise the next step of the identification process.

Materials and methods

The cranium of Poliziano was represented by an extremely deformed parieto-frontal fragment, seven other smaller cranial fragments, and a portion of the face where nearly all of the left maxilla and the entire left zygomatic bone were missing (Fig. 2a). The cranial bones were scanned at the radiology department of Ravenna Hospital by means of computed tomography (CT) performed using a Brilliance 64-slice scanner (Phillips Medical Systems, Eindhoven, The Netherlands) with a slice thickness of 0.9 mm, increment 0.45 mm. At the same time, in the Department of Anatomy, Pharmacology and Forensic Medicine (University of Turin), the skull of a 37-year-old Italian male whose face was morphometrically similar to that of Poliziano was selected for the reference shape and scanned at the Clinic Pinna Pintor of Turin by CT Philips AURA (Phillips Medical Systems, Eindhoven, The Netherlands) with a slice thickness of 1 mm, increment 0.5 mm. The presence of a reference skull in the 3D reconstruction is as essential as in traditional methods of plastic reconstruction. In the present study, the reference skull data are used in the further geometric morphometric manipulations with landmarks and surfaces in order to receive a complete cranium model on the basis of the remains attributed to Angelo Poliziano.

Both three-dimensional digital models (the reference skull and Poliziano cranial fragments) were built using Amira 4.1 (©Mercury Computer Systems, Chelmsford, MA, USA). The models were achieved semi-automatically by threshold-based segmentation, contour extraction, and surface reconstruction (Figs. 1a and 2b).

Identification of landmarks

In PolyWorks® 10.1 (InnovMetric Software, Québec, Canada), 50 anatomical landmarks were identified on the reference skull. On the same model, 22 curves were selected that followed sutures or margins of anatomical structures on the skull, and 144 semilandmarks were selected on them (Fig. 1b; Table 1).

Due to the extreme flattening of the parieto-frontal fragment of the Poliziano cranium, only the facial fragment was considered for the three-dimensional cranial reconstruction. Consequently, fewer landmarks (14) and curves (eight) could be identified on Poliziano's face than on the reference (Table 1; Fig. 2c). Since some of the identified curves were incomplete, a total of 47 semilandmarks were selected on the Poliziano curves.

Homologous landmarks of the reference skull and the Poliziano facial fragment were exported in two distinct.txt files, with missing landmarks of the second one labeled as “x x x” (*x*, *y*, *z* coordinates). The same procedure was followed for the semilandmarks of the curves. Finally, the external surfaces of the reference skull and the Poliziano facial fragment were selected and exported as point clouds.

Reconstruction of the missing data

Due to the availability of only one reference skull, geometric methods were chosen as the primary tool in the reconstruction of missing data [18, 36].

Two methods of the missing data reconstruction on the skull have been previously proposed [18, 36]. One of them, the statistical reconstruction, requires a reference population and takes into account variance and covariance within it. Ultimately, this approach yields best results [18]. An alternative approach, geometric reconstruction, uses properties of the thin-plate spline function and the data about one reference and one target specimen. This method provides for slightly less reliable results and has more dependence on the properties of the reference shape when, as in our case, there are a lot of data missing [18, 36]. It is therefore important to match the reference and target at least by such properties as sex and age. In the absence of the reference population, we have chosen the geometric method of reconstruction.

During the process of reconstruction, we had to address the possibility of deformation in the Poliziano facial fragment. The facial fragment appears anatomically congruous, and it is difficult to establish the amount of deformation, if any, present

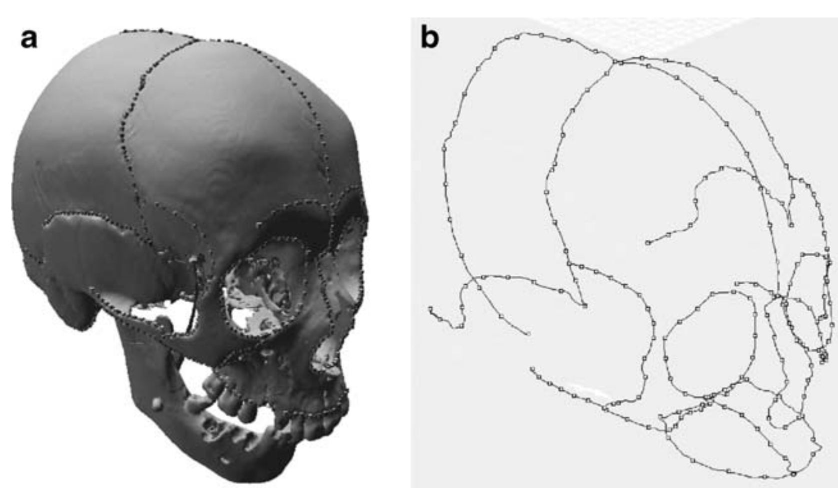


Fig. 1 **a** Three-dimensional digital model of the reference skull: Curves that follow sutures or margins of anatomical features on the skull are displayed; **b** curve and semi-landmarks identified onto the reference skull

Fig. 2 **a** Facial fragment of Poliziano; **b** three-dimensional digital model of the facial fragment of Poliziano; **c** landmarks (*black points*) and curves identified on the facial fragment of Poliziano: Curve numbers are provided in Table 1

Table 1 List of landmarks and curves identified on the 3D models of the reference skull and Poliziano

Number	Landmark name	Number	Landmark name	Number	Curve name	Smlm count[a]
1	Alare left	26	Mastoidale left	1	Metopic[b]	7
2	Alare right[c]	27	Mastoidale right	2	Parietal suture	8
3	Asterion left	28	Maxillo-naso-frontal suture left[c]	3	Lambda-inion	7
4	Asterion right	29	Maxillo-naso-frontal suture right[c]	4	Temporal left	5
5	Auriculare left	30	Mental foramen left	5	Temporal right	5
6	Auriculare right	31	Mental foramen right	6	Squamosal suture right	8
7	Basion	32	Nasion[c]	7	Squamosal suture left	8
8	Bregma	33	Opisthion	8	Lower zygomaticotemporal outline left	7
9	Coronale left	34	Orbitale left	9	Lower zygomaticotemporal outline right	6
10	Coronale right	35	Orbitale right[c]	10	Zygomatic edge left	2
11	Frontomalare orbitale left[c]	36	Palatine corner left	11	Zygomatic edge right[b]	2
12	Frontomalare orbitale right[c]	37	Palatine corner right	12	Zygomaxillare suture left	3
13	Frontomalare temporale left[c]	38	Pogonion	13	Zygomaxillare suture right[b]	3
14	Frontomalare temporale right	39	Prosthion	14	Zygomatic lateral left	4
15	Frontotemporale left	40	Rhinion[c]	15	Zygomatic lateral right[b]	4
16	Frontotemporale right	41	Sphenion left	16	Orbital left[b]	11
17	Glabella[c]	42	Sphenion right	17	Orbital right[b]	11
18	Gnathion	43	Staphylion[c]	18	Nasal[b]	14
19	Gonion left	44	Stephanion left	19	Alveolar	8
20	Gonion right	45	Stephanion right	20	Palatine suture	5
21	Infradentale	46	Subnasale	21	Posterior palatine edge[b]	4
22	Inion	47	Supraorbital notch left[c]	22	Coronal suture	12
23	Lambda	48	Supraorbital notch right[c]		Total semilandmarks on curves	144
24	Lower zygomaticotemporal suture left	49	Zygomaxillare inferior left			
25	Lower zygomaticotemporal suture right	50	Zygomaxillare inferior right[c]			

[a] Semilandmarks identified on the curves

[b] Curves partially digitized on the 3D models of Poliziano's face

[c] Landmarks identified on the 3D models of Poliziano's facial bone

in the face. An experimental attempt of reflecting the right side of the face and fitting it to the left was not successful as the remains of the left orbit and the reflection of the right orbit did not fit together. The mismatch may have occurred as a result of the deformation or as normal bilateral asymmetry of the human face [37–39]. Given the poor preservation of the left side of the face, there was no possibility to recreate the original facial structure that would account for the natural bilateral asymmetry. Therefore, we proposed reconstruction of a symmetrical face which would approximate the original.

We have considered two reconstruction options. The first one provides a consensus shape between the original Poliziano fragment with missing data reconstructed and its reflection. Ultimately, the information from both right and left sides is preserved in this model assuming that no deformation is present on either side. The second reconstruction was obtained by replacing the left side for the reflection of the right side of the face so that the left facial part is disposed of. In this case, it was assumed that the original lacked deformation only on the right side.

The flow of computation involved a number of procedures applied for reconstruction of the missing cranial data by Gunz [36]. Practically, we used formulae developed by P. Gunz and P. Mitteroeker and described by Gunz [36] and for Mathematica 5.2 (©1988–2005 Wolfram Research, Champaign, IL, USA).

These procedures are summarized in several steps.

1. A reflection for the surface, landmarks, and curve semilandmarks of the Poliziano face was obtained. Paired landmarks and semilandmarks on reflection were re-labeled so that the homology with the original was restored.
2. Geometric homology for semilandmarks on curves was achieved between the reference skull and Poliziano on one hand and the reference skull and the reflection on the other. This step involved relaxing (sliding along tangent vectors) semilandmarks on the reference against the preserved semilandmarks in Poliziano and its reflection in turn so that the semilandmarks on different models would find themselves in geometrically homologous positions. The relaxation (sliding) procedure and discussion of its biological impact are given by Gunz et al. [36, 40]. Two models have been obtained: (a) semilandmarks on the reference relaxed against Poliziano and (b) semilandmarks on the reference relaxed against reflection. The relaxed semilandmarks were projected back onto the surface of the reference individual for each of the models.
3. The third step involved reconstruction of the missing data in the original Poliziano and its reflection. In order to do so, the relaxed reference shapes were warped (see below) onto the preserved landmarks and semilandmarks in Poliziano and its reflection accordingly. The warping procedure utilizes properties of the thin-plate spline function. In this case, the existing homologous landmarks are superimposed, whereas data between them are estimated so as to minimize the bending energy matrix of the shape [36, 40, 41]. The resulting estimations for Poliziano and its reflection contained a complete set of landmarks and semilandmarks for the whole cranium. To achieve a better fit for the estimated surface, semilandmarks whose position fell onto the preserved surface in Poliziano and its reflection were projected onto the respective surfaces. At the end of this step, we have obtained two maximally fitted datasets of the landmarks and semilandmarks for the complete Poliziano skull and its reflection.
4. A consensus shape between Poliziano and its reflection was calculated. In order to do so, we first achieved geometric homology of semilandmarks between the complete Poliziano dataset, its reflection, and the reference model by relaxing semilandmarks on both Poliziano and reflection against the reference. After this step, a consensus shape was obtained as an average between the complete skulls for Poliziano and its reflection after Procrustes superimposition without removal of the size variable. Ideally, the consensus shape between the original and its reflection corrects for the bilateral asymmetry in the object [42, 43]. The possibility of an error introduced in this reconstruction due to the properties of the thin-plate spline function is discussed below [18, 36].
5. The second reconstruction of the complete cranium is received by means of Procrustes superimposition of the Poliziano model and its reflection followed by the replacement of the left paired landmarks and semilandmarks in Poliziano by their counterparts in the reflection. The full size is then restored to the centroid size of the original Poliziano model.

Text files containing coordinates for all landmarks and semilandmarks on the two reconstructed Poliziano models and on the reference shape after sliding were obtained for further processing in Amira software. The 314 landmarks of the reference skull as well as the 314 reconstructed landmarks of Poliziano were imported from the previously received Amira format text files (Fig. 3a, b). The surface of the reference skull was then warped onto the landmarks and semilandmarks of the Poliziano reconstruction with the help of the Bookstein transformation mode based on the thin-plate spline method [41] (Fig. 3c). Bookstein mode guarantees that all landmarks will be transformed exactly to their corresponding points, and the nearest neighbor interpolation is used for resampling the final model.

All of the 314 landmarks and semilandmarks of the reference skull were thus transformed into the corresponding landmarks and semilandmarks for the two complete models

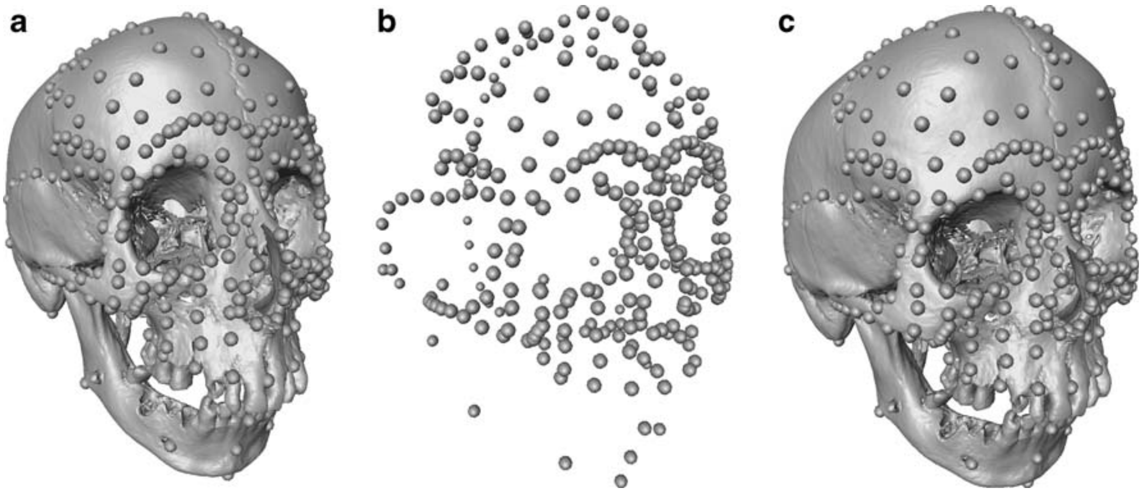


Fig. 3 **a** The 314 landmarks on the reference skull; **b** the 314 reconstructed landmarks for Poliziano; **c** three-dimensional digital model of Poliziano skull obtained by warping the 314 landmarks of the reference skull into the correspondent landmarks of Procrustes consensus (model A)

of Poliziano's skull, whereas the surface of the reference skull was automatically warped so as to minimize the bending energy of the according transformation [41]. Two final surface models were obtained by the warping procedure: Model A represents a symmetric version of the Poliziano skull achieved as a consensus between the original warped shape for the complete Poliziano and its reflection. This reconstruction, therefore, averages information on both sides of the face diminishing the amount of deformation, if present on either side (Fig. 3c); model B, a symmetric model of the Poliziano skull, in which the potential deformation on the right has not been removed and the left side is reconstructed as reflection of the right with the loss of all information on its original configuration.

Cranium/painting superimposition

In order to verify the correspondence between the warped skulls and the real facial fragment of Poliziano, we superimposed their surfaces and visualized deviation of the reconstructed face by color coding the differences in the Inspect module of PolyWorks. The mandible has been removed from models A and B, and only the cranium is considered in the subsequent analysis (Fig. 4a, c). The superimposition was performed using iterative closest point, an algorithm that minimizes the distance between two point clouds by the least squares method [44, 45].

In both models (A and B), a good correspondence was displayed in the frontal bone as well as in the right frontal process of the maxilla (Fig. 4b, d). In model A, the portion around the zygomatic-maxilla suture was more divergent, where a deviation of about 3–4 mm was detected (Fig. 4b). In model B, a large difference was found in the left lateral orbital process of the frontal bone, where the real facial fragment of Poliziano deviated by about 6 mm (Fig. 4d).

Both models (A and B) have been compared with the paintings of the historical character by means of virtual superimposition. Given that Poliziano died at the age of 40, the portraits of a middle-aged Poliziano depicted by Domenico Ghirlandaio (1449–1494) and Theodor de Bry (1528–1598) were chosen (the first one form the Tornabuoni Chapel, in the church of Santa Maria Novella, Florence; the latter from the Bibliotheca Calchographica di Jean Jacques Boissard). It is worthwhile to note that since Ghirlandaio worked when Poliziano was still alive, his paintings are considered more reliable than the portrait depicted by de Bry about 50 years later. Furthermore, in contrast to some other paintings of Poliziano that show him in lateral view (i.e., a painting of Domenico Ghirlandaio, “Storie di San Francesco”, from Sassetti Chapel in Santa Trinità, Florence, and Sandro Botticelli (1445–1510) “Adorazione dei Magi”, Galleria degli Uffizi, Florence), the portraits of Ghirlandaio and de Bry that we have chosen for the cranium/painting superimposition painted a fronto/lateral view of Poliziano's face, therefore providing better conditions for the superimposition method. Unfortunately, the two portraits present substantially different physiognomic features of Poliziano's face (mainly in the forehead and in the zygomatic bones) so that we could not presume to reach a positive identification with certainty.

Before carrying out cranium/portrait superimposition, an intermediate step of orientation was necessary in order to augment the reliability of the result and guide the superimposition process itself. Thus, in the Imedit module of PolyWorks, models A and model B were oriented in the Frankfurt plane and a midsagittal plane was created (Fig. 5a). According to the Manchester protocol used in forensic anthropology for facial reconstruction [9–11], craniometric points were virtually placed on the models anchoring normal vectors to the surface. Instead of using all 34 points of the Manchester

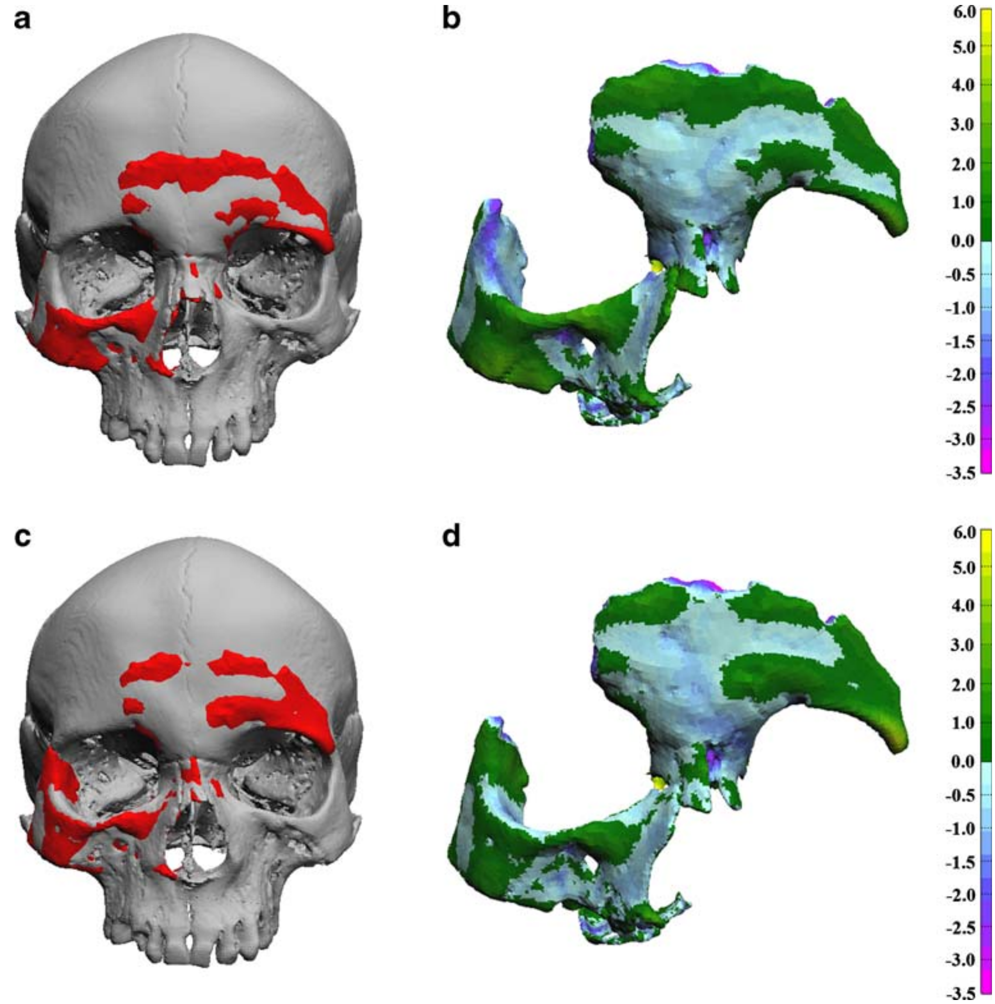


Fig. 4 **a** Superimposition between model A and the three-dimensional digital model of the Poliziano's facial fragment; **b** their error deviation analysis: Divergences are detected in the zygomatic-maxillary region; **c** superimposition between model B and the three-dimensional digital model of the Poliziano's facial fragment; **d** their error deviation analysis: The left lateral orbital process of the frontal bone displays the major deviation between the two models

protocol [9–11], only ten craniometric points (five paired and five unpaired) were selected for our purposes.

Since on the portrait Poliziano's face is turned to the right, points were selected on the right side of the models in order to guide the subsequent cranium/painting superimposition process (midsagittal points: ophryon, glabella, nasion, rhinion, subnasale; points on the right: lateral forehead, lateral orbit, orbitale, canine fossa, lateral zygomatic).

Then, cylinders were constructed from vectors, reproducing tissue depth markers regularly used in forensic facial reconstruction [11] (Fig. 5b). Each cylinder was edited so that its axis is formed by a corresponding vector and the length

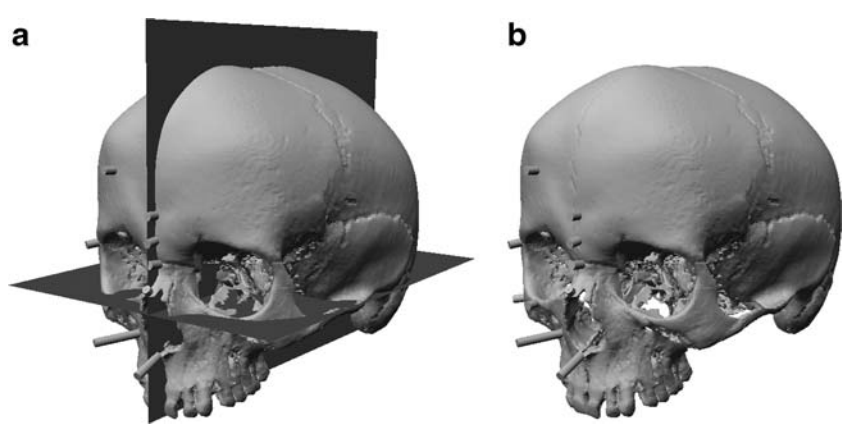


Fig. 5 **a** Frankfurt plane and midsagittal plane identified in model A; **b** cylinders reproducing tissue depth markers were constructed onto the surface of model A

calculated in accordance with the mean flesh thicknesses in an adult white European male of 40–49 years of age [11].

Results

The paintings depicted by Domenico Ghirlandaio and Theodor de Bry and the two digital models with cylinders (named Ac and Bc) were imported in Amira for cranium/painting superimposition. In order to assist the superimposition process, eight landmarks were selected on the portraits in relation to points easily recognizable on the cranium: mesial and upper point of the left orbit, right and left ectocanthion, tip of the nose, nasion, glabella and ophryon (Fig. 6).

Using transformation editor options, the cranium was translated directly onto the pictures, and dynamic orientation and uniform sizing processes were used to arrive at the best possible alignment of the cranium and the portraits of Poliziano. The visualization was set to orthographic camera in order to exactly align objects in 3D space. Following suggestions by Fenton et al. [8], particular attention was paid to aligning the left and right Whitnall's tubercles of the cranium with the left and right ectocanthion points of the face. Alignment of the tip of the tissue depth marker at the subnasal point and the tip of the nose were also considered. Given the particular orientation of the face on the portrait, further adjustments of the cranium position were necessary so that landmarks on the cranium would align with “corresponding” landmarks on the face. The points identified on the left orbit of the portrait have been located in positions approximately corresponding with the equivalent points on the skull. Although they cannot be considered proper anatomical landmarks, they aided the process of cranium orientation and sizing.

For both portraits, better results were obtained using model Ac (Figs. 7 and 8). Without considering the neurocranium, the main differences between the two models were emphasized in the right and left orbital portion as well as in the right zygomatic bone, while less differences concern the midsagittal landmarks.

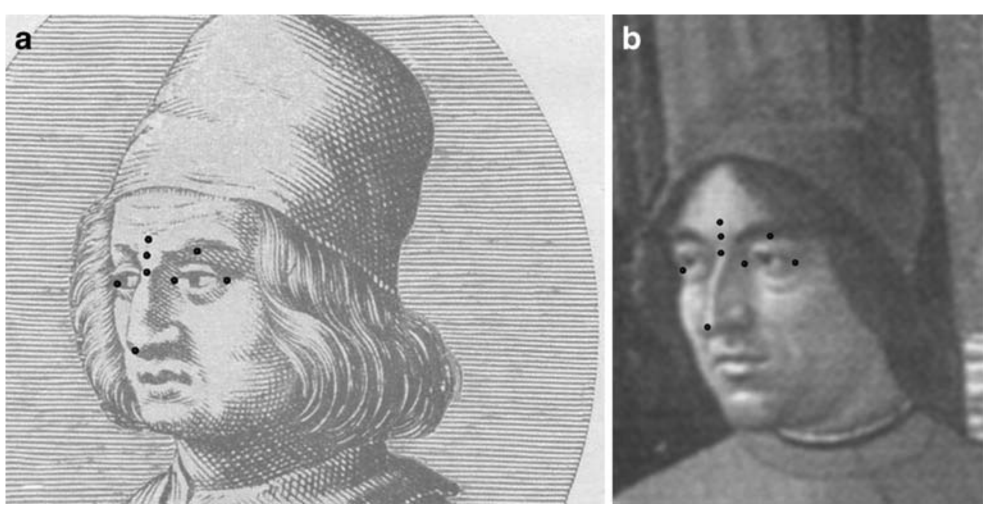
With respect to model Ac, the four cylinders on the midsagittal plane of the cranium correspond well with the landmarks of the portraits (Fig. 7). In detail, the correct size of the left orbit has been recognized mainly in the portrait of de Bry (Fig. 7a, b), an accurate face/cranium proportion has been achieved in both the portaits from the ophryon to the tip of the nose, and the incisors are contained behind the upper lip so that the incisive edge reaches the upper part of the lower lip. Nevertheless, some inconsistencies were observed due to mismatch between the two portraits. In fact, the orthognathic frontal bone of model Ac fit properly with the forehead profile of de Bry's portrait (Fig. 7a, b), unlike the flatter receding forehead painted by Ghirlandaio (Fig. 7c, d). On the other side, the high position of the zygomatic bones of model Ac is more consistent with the depiction made by Ghirlandaio.

Apart from some features also recognized in model Ac, i.e., the orthognathic frontal bone (similar to de Bry'painting) and the high position of the zygomatics (as Ghirlandaio's painting), when model Bc was superimposed onto the portraits (Fig. 8), some other features emphasized that model Bc is less successful than model Ac. For example, the left orbit is too large, the right zygomatic bone runs out of the border of the face mainly in Ghirlandaio's painting (Fig. 8c, d), and the lateral border of the right orbit is pushed too far backward (Fig. 8a, b).

Discussion

It is well known that human remains recovered from the ground could miss important portions of the skull so that the identification procedure based on skull/photo superimposition

Fig. 6 Portrait depicted by Theodor de Bry (**a**) and Domenico Ghirlandaio (**b**) and landmarks used for adjustments of the cranium position



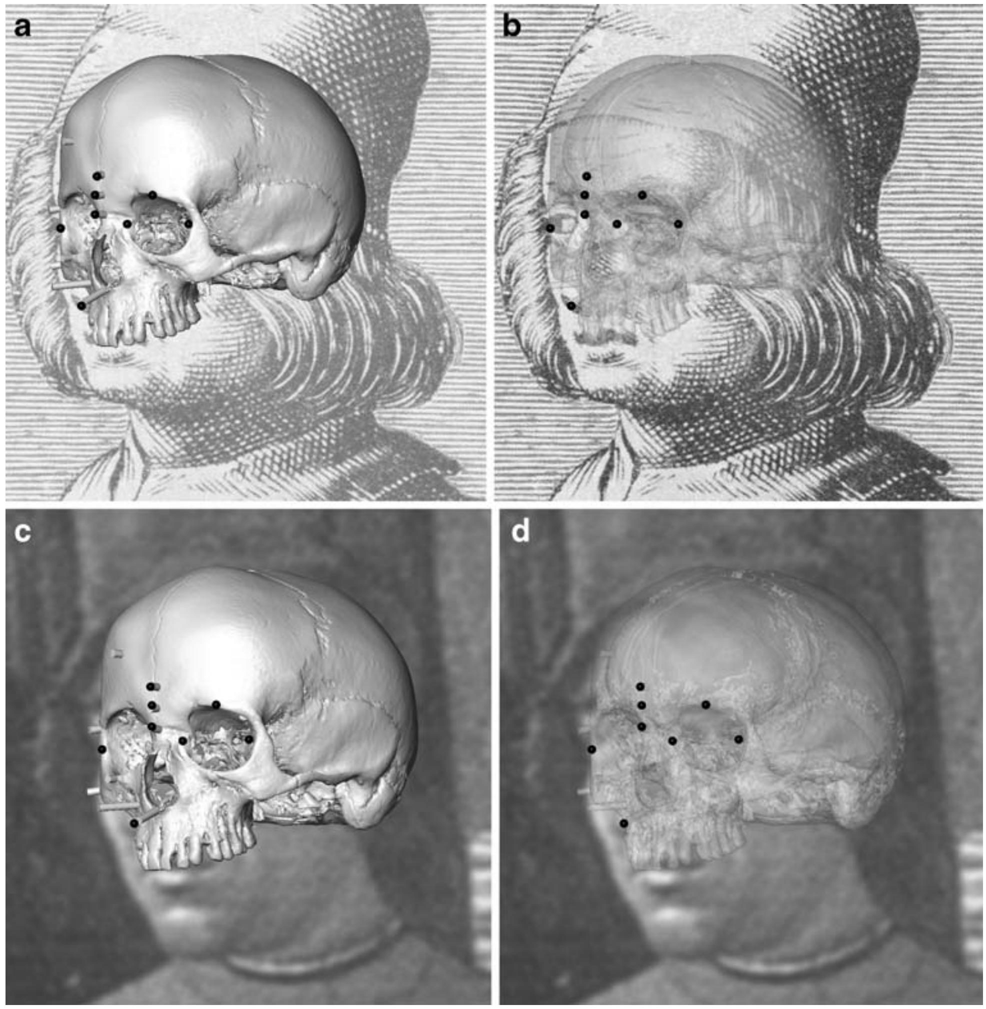


Fig. 7 Superimposition of model Ac to the portrait depicted by Theodor de Bry (**a** without transparency; **b** with transparency) and Domenico Ghirlandaio (**c** without transparency; **d** with transparency); landmarks positioned in the midsagittal plane have good relationship with the correspondent cylinders of model Ac

[4–8] and facial reconstruction [9–13] could be significantly compromised. The reconstruction of damaged skulls is usually performed by means of physical replacement of missing portions. An accurate reconstruction relies on the characteristics of the available part such as its morphology, size, and deformation. Usually, the smaller and fewer fragments that are available, the less reliable the reconstruction result is. A plastic reconstruction of the lost and fragmented bones of an individual's facial features carried out by an expert is normally the most reliable and frequently applied approach. Unfortunately, depending on the difficulty of the case, the plastic reconstruction can take considerable time. This limitation can be partly overcome with the help of the three-dimensional digital models and GMM if those are applied in conjunction with the traditional morphological assessment of the original and the resultant reconstruction. Moreover, the computerized approach provides with a benefit of easy manipulation of the reconstruction and, for example, the picture of the identified individual in virtual environment. The assumptions behind the geometric morphometric approach are known, and therefore, the reliability of the final result may be predicted.

The fragmentation and unconfirmed partial deformation of the cranial remains attributed to Angelo Poliziano provided the pretext to employ GMM to reconstruct the cranium. Since attribution of the skeleton remains to Angelo Poliziano was questionable, it was needed to confirm his identity by means of cranial/painting superimposition method that would be analogous to the skull/photo superimposition technique generally used in forensic anthropology.

Both obtained virtual reconstructions performed well in superimposition with the surface of the preserved facial fragment and partially with the paintings. However, both of them have intrinsic imperfection related to the properties of the thin-plate spline function. The thin-plate spline function bends the spline in the vicinity of the existing landmarks and is best at prediction of the missing data in the proximity of the preserved parts. However, if there are no landmarks preserved to bend the spline in the vicinity of the missing landmarks, i.e., if the estimation occurs some distance from the preserved part, then the thin-plate spline grid is almost square [36]. In other words, the further the location of the estimated landmarks from the preserved surface, the closer they resemble the reference shape. As a result, the

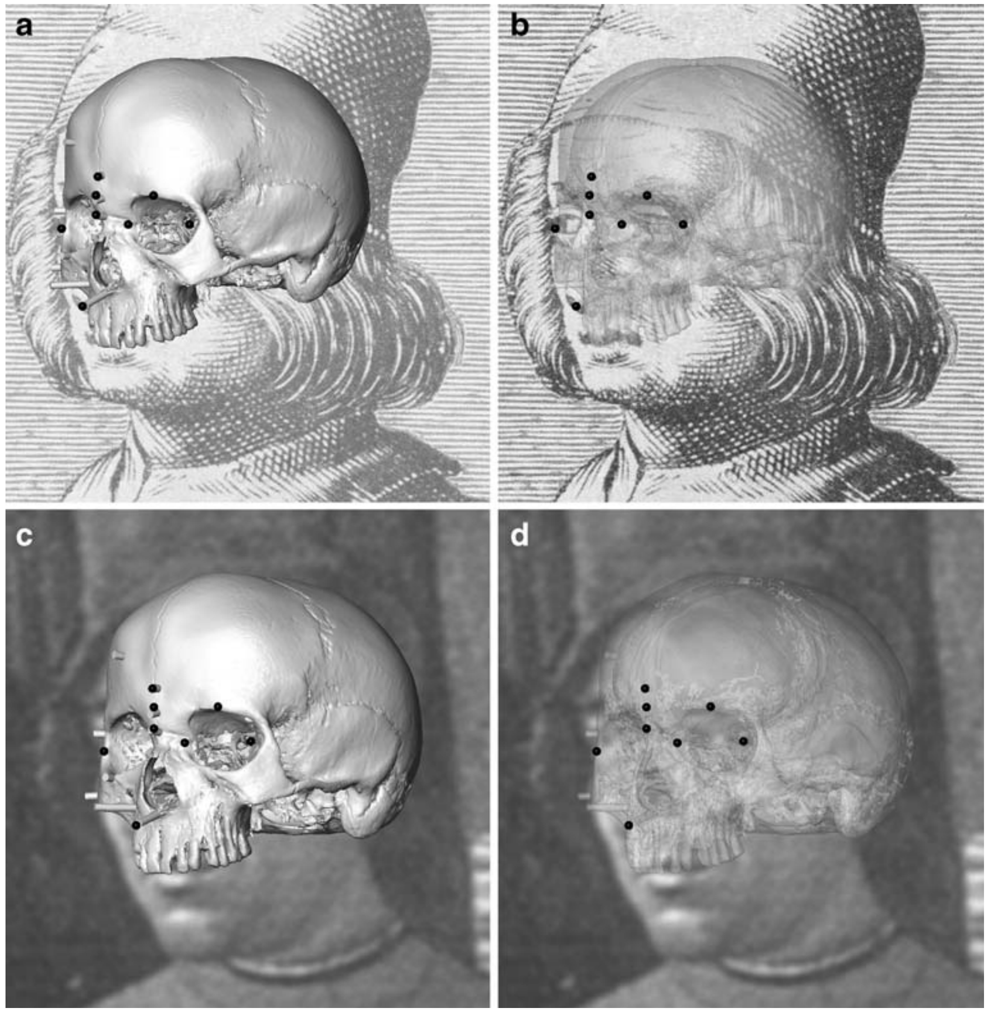


Fig. 8 Superimposition of model Bc to the portrait depicted by Theodor de Bry (**a** without transparency; **b** with transparency) and Domenico Ghirlandaio (**c** without transparency; **d** with transparency); some defects are noticeable in the right zygmatic bone as well as in the left orbit of model Bc

reconstruction of the neurocranium, however practical in the sense of the further application for the facial features reconstruction, is not reliable in our case. For the same reason, the mandible was removed and was not considered in the skull/picture superimposition.

Further characteristics of the received models include removal of the natural bilateral asymmetry of the face. Moreover, the face of model A ultimately incorporates information not only about the remaining parts of Poliziano and the reliably reconstructed portions of the face in the vicinity of the existent landmarks and semilandmarks. This face also includes information about the relatively remote lateral part of the left zygomatic, which is already less reliable and resembles the reference shape. In addition, the method of finding a consensus between the skull and its reflection is not a remedy for deformation. If present, the deformation is averaged across the sides, and the final outcome is largely dependent on the magnitude and direction of the deformation. However, in the case of Poliziano's face, we found that the consensus method was useful due to the subtlety of the deformation if at all present.

Model B is free of the problems that arise with the calculation of a consensus shape. However, it preserved the original geometry only of the right side of Poliziano's face. This model turned out to have a broader left orbit than model Ac and an even more protruding zygomatic bone as it has been shown in the superimposition with the paintings.

The step of the cranium/painting superimposition has been relatively simple in the virtual environment. The usual technique of the computer-based skull/photo superimposition requires standard equipment such as two video cameras, an electronic mixing device, and a standard monitor of high resolution for viewing [8, 46]. In our case, the orientation and sizing of the two cranial models (Ac and Bc) in comparison with the portraits of Poliziano by Domenico Ghirlandaio and Theodor de Bry as the references were carried out in fully virtual environment. A better fit with the portraits has been shown by model Ac. This result may be due to the presence of some deformation on the right side of the preserved fragment that was averaged out in the consensus shape (model Ac) but led to the failure of model Bc to fit the portrait perfectly.

Since the uncertainty regarding the reliability of the different portraits and the mismatch among them, we cannot claim to provide a positive identification of Angelo Poliziano. Nevertheless, given that a good correspondence was observed between the tissue depth markers (represented by cylinders) and the points identified on the portrayed face, the probability that the facial fragment discovered in the S. Marco cloister (Florence, Italy) in July 2007 actually belongs to the Italian humanist Angelo Poliziano cannot be excluded.

In conclusion, the presented attempt at reconstruction of the cranium and its superimposition with paintings for the identification of Angelo Poliziano is an example of the multidisciplinary integration of anatomical and morphological expertise with virtual computer modeling techniques. We suggest that the application of this approach can become a valuable tool in forensic anthropology.

Acknowledgments We thank Philipp Gunz for providing the formulae that he developed in order to reconstruct missing data in Mathematica. We wish to express our thanks to the staff of the Radiology Department of Ravenna Hospital (Ravenna, Italy) and Clinica Pinna Pintor (Turin, Italy), in particular to Dr Gino Carnazza, for support in this project on the technical aspects of CT scanning. Thanks to Prof. Giacomo Giacobini for help in the choice of the reference skull. Many thanks to Stephanie Kozakowski for copy editing our manuscript. This work was supported by EU Marie Curie Training Network MRTN-CT-2005-019564 EVAN.

References

1. Işcan MY, Solla HE, McCabe BQ (2005) Victim of a dictatorial regime: identification of Mr. Roberto Gomensoro Josman. Forensic Sci Int 151:213–220
2. Ferenbach D, Schwidetzky I, Stloukal M (1980) Recommendations for age and sex diagnosis of skeletons. J Hum Evol 9:517–550
3. De Angelis D, Cattaneo C, Grandi M (2007) Dental superimposition: a pilot study for standardising the method. Int J Legal Med 121:501–506
4. Işcan MY, Helmer RP (1993) Forensic analysis of the skull: craniofacial analysis, reconstruction and identification. Wiley, New York
5. Yoshino M, Matsuda H, Kubota S, Imaizumi K, Miyasaka S, Seta S (1997) Computer-assisted skull identification system using video superimposition. Forensic Sci Int 90:231–244
6. Ghosh AK, Sinha P (2001) An economised craniofacial identification system. Forensic Sci Int 117:109–119
7. Solla HE, Işcan MY (2001) Skeletal remains of Dr. Eugenio Antonio Berrios Sagredo. Forensic Sci Int 116:201–211
8. Fenton TW, Heard AN, Sauer NJ (2008) Skull–photo superimposition and border deaths: identification through exclusion and the failure to exclude. J Forensic Sci 53:34–40. doi:10.1111/j.1556-4029.2007.00624.x
9. Prag J, Neave R (1997) Making faces. British Museum, London
10. Taylor KT (2001) Forensic art and illustration. CRC, New York
11. Wilkinson C (2004) Forensic facial reconstruction. Cambridge University Press, Cambridge
12. Wilkinson C, Neave R (2003) The reconstruction of a face showing a healed wound. J Arch Sci 30:1343–1348
13. Quatrehomme G, Balaguer T, Staccini P, Alunni-Perret V (2007) Assessment of the accuracy of three-dimensional manual craniofacial reconstruction: a series of 25 controlled cases. Int J Legal Med 121:469–475
14. Claes P, Vandermeulen D, De Greef S, Willems G, Suetens P (2006) Craniofacial reconstruction using a combined statistical model of face shape and soft tissue depths: methodology and validation. Forensic Sci Int 159:147–158
15. Vandermeulen D, Claes P, Loeckx D, De Greef S, Willems G, Suetens P (2006) Computerized craniofacial reconstruction using CT-derived implicit surface representations. Forensic Sci Int 159:164–174
16. Lee K (1999) Principles of CAD CAM CAE systems. Addison-Wesley, Boston
17. Petronilli S (2002) Prototipazione rapida, ingegneria inversa, beni culturali. Innovare 2:28–34
18. Gunz P, Mitteroecker P, Bookstein FL, Weber GW (2004) Computer aided reconstruction of incomplete human crania using statistical and geometrical estimation methods. Enter the Past: Computer Applications and Quantitative Methods in Archaeology, BAR International Series 1227. Archaeopress, Oxford, pp 92–94
19. Fantini M, De Crescenzio F, Persiani F, Benazzi S, Gruppioni G (2006) Computer assisted archaeo-anthropology on damaged mummified remains. Project papers from the joint event CIPA/VAST/EG/EuroMed 2006: The evolution of Information Communication Technology in Cultural Heritage, pp 112–118
20. Benazzi S, Fantini M, De Crescenzio F, Mallegni G, Mallegni F, Persiani F, Gruppioni G (2008) The face of the poet Dante Alighieri reconstructed by virtual modelling and forensic anthropology techniques. J Archaeol Sci 36:278–283. doi:10.1016/j.jas.2008.09.006
21. Eckardt A, Swennen GR (2005) Virtual planning of composite mandibular reconstruction with free fibula bone graft. J Craniofac Surg 16:1137–1140
22. Mann F, Gatinel D, Morax S, Hoang-Xuan T (2006) Three-dimensional computer-assisted modeling of the orbital cavity and the eyelids. J Fr Ophtalmol 29:381–390
23. Poukens J, Haex J, Riediger D (2003) The use of rapid prototyping in the preoperative planning of distraction osteogenesis of the cranio-maxillofacial skeleton. Comput Aided Surg 8:146–154
24. Marchetti C, Bianchi A, Bassi M, Gori R, Lamberti C, Sarti A (2006) Mathematical modeling and numerical simulation in maxillo-facial virtual surgery (VISU). J Craniofac Surg 17:661–667
25. Zollikofer CPE, Ponce de Leon MS, Martin RD, Stucki P (1995) Neanderthal computer skulls. Nature 375:283–285
26. Ponce de León MS, Zollikofer CPE (1999) New evidence from Le Moustier 1: computer-assisted reconstruction and morphometry of the skull. Anat Rec 254:474–489
27. Neubauer S, Gunz P, Mitteroecker P, Weber GW (2004) Geometric reconstruction of the MLD 37/38 endocranium. Am J Phys Anthropol Suppl 38:152
28. Zollikofer CPE, Ponce de León MS, Lieberman DE et al (2005) Virtual cranial reconstruction of Sahelanthropus tchadensis. Nature 434:755–759
29. Ogihara N, Nakatsukasa M, Nakano Y, Ishida H (2006) Computerized restoration of nonhomogeneous deformation of a fossil cranium based on bilateral symmetry. Am J Phys Anthropol 130:1–9
30. Frassetto F (1933) Dantis ossa. La forma corporea di Dante, Bologna
31. Pearson K, Morant GM (1934) The Wilkinson head of Oliver Cromwell and its relationship to busts, masks and painted portraits. Biometrika 1934(26):1–116
32. Fabroni A (1800) “Elogj di Dante Alighieri, di Angelo Poliziano, di Lodovico Ariosto, e di Torquato Tasso”. Stamperia Reale, Pre-1801 Imprint Collection (Library of Congress), pp 142–143

33. Cantù C (1865) “Storia della letteratura italiana”. F. Le Monnier, p 140
34. Andreolli B (1994) Ioannis Pici Mirandulae viri omni disciplinarum genere consumatissimi vita per Ioannem Franciscum illustris principis galeotti Pici filium conscripta. Aedes Muratoriana, Modena
35. Giovio P, Caruso C (1999) Ritratti degli uomini illustri. Sellerio, Palermo, p 119
36. Gunz P (2005) Statistical and geometric reconstruction of hominid crania: reconstructing australopithecine ontogeny. PhD Thesis. Ph. D. Dissertation
37. Gawlikowska SA (2006) Radiological and anthropometric analysis of the symmetry and direction of evolution of skulls from some historic populations. Ann Acad Med Stetin 52:107–117
38. Gawlikowska A, Szczurowski J, Czerwiński F, Miklaszewska D, Adamiec E, Dzieciołowska E (2007) The fluctuating asymmetry of medieval and modern human skulls. Homo 58:159–172
39. Deleon VB (2007) Fluctuating asymmetry and stress in a medieval Nubian population. Am J Phys Anthropol 132:520–534
40. Gunz P, Mitteroecker P, Bookstein FL (2005) Semilandmarks in three dimensions. In: Slice DE (ed) Modern morphometrics in physical anthropology. Kluwer Academic, New York, pp 73–98
41. Bookstein FL (1991) Morphometric tools for landmark data. Geometry and biology. Cambridge University Press, New York
42. Mardia KV, Bookstein FL, Moreton IJ (2000) Statistical assessment of bilateral symmetry of shapes. Biometrika 87:285–300
43. Dryden IL, Mardia KV (1998) Statistical shape analysis. Wiley, London
44. Besl PJ, McKay ND (1992) A method for registration of 3-d shapes. PAMI 14:239–256
45. Zhang ZY (1994) Iterative point matching for registration of free-form curves and surfaces. Int J Comput Vision 13:119–115
46. Ubelaker DH, Bubniak E, O'Donnell G (1992) Computer-assisted photographic superimposition. J Forensic Sci 37:750–762