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Review article

# Computerized craniofacial reconstruction: Conceptual framework and review

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ABSTRACT

When confronted with a corpse that is unrecognizable due to its state of decomposition, soft-tissue mutilation or incineration, and if no other identification evidence is available, craniofacial reconstruction (CFR) can be a useful tool in the identification of the body. Traditional methods are based on manual reconstruction by physically modelling a face on a skull replica with clay or plasticine. The progress in computer science and the improvement of medical imaging technologies during recent years has had a significant impact on this domain. New, fast, flexible and computer-based objective reconstruction programs are under development. Employing the newer technologies and permanently evaluating the obtained results will hopefully lead to more accurate reconstructions, beneficial to the added value of CFR methods during crime-scene investigations. A general model-based workflow is observed, when analysing computerized CFR techniques today. The main purpose of this paper is to give an overview of existing computer-based CFR methods up to date defined within a common framework using a general taxonomy. The paper will also discuss the various alternatives and problems which arise during the process of designing a CFR program.


**Contents**



## 1. Introduction

The identification of an unknown body is obtained by forensic identification techniques which are predominantly based on comparisons of ante- and post-mortem data, such as medical files, dental records, X-rays or DNA. The identification procedure becomes more difficult when dealing with skeletonised human remains, where identifying features may have decomposed or are missing. In these circumstances, a *craniofacial reconstruction* (CFR) may assist the investigation out of the impasse. The goal of craniofacial reconstruction is to recreate a likeness of the face of an individual at the time of death. Different 2D and 3D manual or

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computer-aided facial reconstruction techniques have been developed for this purpose and all are based on the assumed relationship between the soft-tissue envelope and the underlying skull substrate.

Several 3D manual methods for facial reconstruction are currently being used in practice. These reconstructions consist of physically modelling a face on a skull replica (the target skull) with clay or plasticine. The Russian anthropologist Gerasimov [1] was one of the first to make a manual reconstruction by modelling the complete anatomy of muscles and soft-tissues covered by a thin layer, mimicking skin, onto the skull. This anatomical or "Russian" technique, also referred to as the *morphoscopic* technique, was further refined by Lebedinskaya et al. [2]. During the same period, an alternative technique was developed in the United States, called the *morphometric* method [3]. This technique consists of building the soft-tissue layers in bulk, without much regard to the detail of the underlying anatomy, approximating tabulated average tissue-depths at a sparse set of landmarks on the skull and interpolating in between. More recently, Neave [4] used both Russian and American methods laying the foundation for the *combined* technique, which was further developed by Wilkinson [5] and her team at Manchester. Proponents of this method claim that since the face is reconstructed according to the rules of anatomy, artistic subjectivity in areas with limited tissue depth measurements is reduced.

Manual reconstruction methods, however, require a high degree of anatomical and artistic modelling expertise and as a result remain difficult and subjective. The interpretations of two different artists always result in the creation of two different faces from the skull where the differences vary widely. According to Davy et al. [6] this point is further illustrated in Ref. [7], in which multiple facial reconstructions of several victims from the Green River serial-killer were created. The results were highly variable between practitioners and little success was achieved when the reconstructions were shown to the public in an attempt to provoke recollections from people who might have known the deceased during live. Furthermore, these reconstructions are time consuming, and are therefore often limited to a single reconstruction.

The progress in computer science and the improvement of medical imaging technologies during recent years has lead to the development of alternative computer-based CFR methods. A computer, compared to a human expert, is consistent and objective. Knowing all the modelling assumptions and given the same input data, a computer always generates the same output data. Furthermore, certain procedures can be automated such that the creation of multiple reconstructions from the same skull using different modelling assumptions (age, BMI, ancestry, gender, ...) becomes possible. As a result, the CFR process becomes accessible to a wide range of people without the need for extensive expertise. An additional advantage of using computers is the ease of visualization. The skull and the reconstructed face can be visualized together by making the face transparent, such that the face–skull relationship can be examined and, if necessary, corrected. The development of software for computerized facial reconstructions of an individual would be of benefit to various law enforcement agencies, by allowing faster, easier and more efficient generation of multiple representations of an individual.

Current computerized techniques all share the same general model-based workflow depicted in Fig. 1. They are essentially a virtual mimicking of manual reconstruction techniques and can be compartmentalized into six components (a–f). Firstly, the unknown skull is examined by anthropological and dental experts (a) to determine properties like age, gender and ancestry affiliation. Then, a virtual skull copy (b) is obtained by digitizing the real skull. The core of every technique lies within the craniofacial model (CFM) (c) used, which codes for the a-priori knowledge about faces and their link to the underlying skull substrates. The CFM is the equivalent of the expert performing a manual reconstruction. The anthropological properties influence or tailor the CFM. A reconstruction (e) is then obtained by finding the geometrical relationship between the CFM and the unknown skull based on an appropriate choice of skull representation (d). In

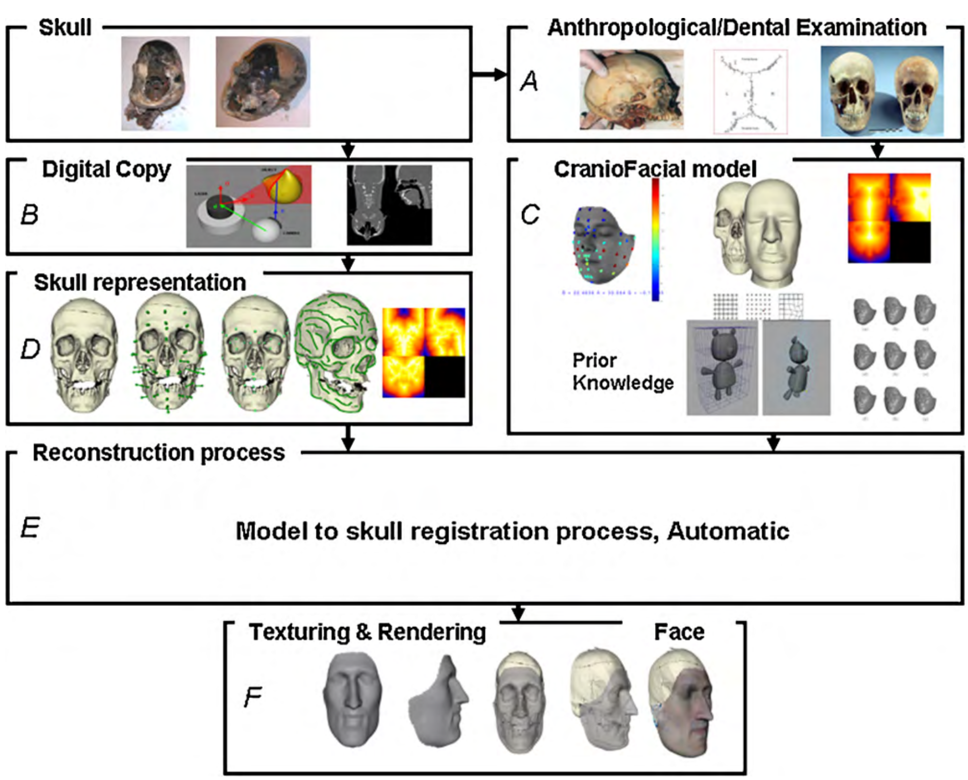


**Fig. 1.** General workflow of computerized craniofacial reconstruction techniques.

**Table 1**
Enlisting of 3D computerized CFR techniques over the past 20 years in a quasi chronological order.

| Method | Reference | Craniofacial model (CFM) | | | | Target skull representation |
|---|---|---|---|---|---|---|
| | | Template (CFT) | | Information (CFI) | Deformation (CFD) | |
| | | What | Type | | | |
| Vanezis | [14] | P | Single/specific | Face | Generic/non-uniform scaling | Sparse/tissue dowels + growth |
| | [40] | H | Single/specific | Face | Generic/– | Sparse/tissue dowels |
| Evenhouse | [41] | P | Single/– | Face | Generic/polygon based deformations | Sparse/tissue dowels |
| Evison | [16,17] | H | Single/specific | Face | Generic/– | |
| Micheal | [42] | H | Single/specific | Face | Generic/volume distortion functions | |
| Shahrom | [15] | H | Single/generic | Face | Generic/– | Sparse/tissue dowels |
| Archer | [43,44] | H | Single/generic | Face | Generic/radial basis functions | Sparse/tissue dowels |
| Quatrehomme | [35] | H | Single/specific | Face/skull | Generic/radial basis functions | Dense/crest-lines |
| Seibert | [45] | H | Single/specific | Face/skull | Generic/radial basis functions | Dense/feature points |
| Nelson | [46] | H | Single/specific | Face | Generic/local cylindrical coordinate | Dense/feature points |
| Attardi | [27] | H | Single/specific | Face/skull | Generic/diffused scattered motion fields | Sparse/tissue dowels + extra |
| Bullock | [29] | H | Single/generic | Face | Generic/radial basis functions | Sparse/tissue dowels + growth |
| Plasencia | [30] | H | Single/– | Face | Generic/polygon based deformations | Sparse/tissue dowels + growth |
| Jones | [47] | H | Single/specific | Face/skull | Generic/– | Dense/feature points |
| Kahler | [22] | H | Single/generic | Face/muscles | Generic/– | Sparse/tissue dowels |
| Claes | [18,26,31–34] | H | multiple/generic | Face/tissue thicknesses | Face-specific/PCA | Sparse |
| | [21,38] | H | Multiple/generic | Face/tissue thicknesses | Face-specific/PCA | Implicit/signed distance transform |
| Vandermeulen | [37,48] | H | Multiple/specific | Face/skull | Generic/digital cosine transformations | Implicit/signed distance transform |
| | [49] | H | Multiple/specific | Face/skull | Generic/radial basis functions | Implicit/signed distance transform |
| Pei | [50] | H | Single/generic | Face/skull | Generic/radial basis functions | |
| | [51] | H&P | Single/specific | Face | Generic/– | Dense/range image |
| Andersson | [28] | P | Single/generic | Face | Generic/– | Sparse/tissue dowels + growth |
| Berar | [52–54] | H | Multiple/generic | Face/skull | Face-specific/PCA | Dense/feature points |
| Davy | [6] | P | Single/generic | Face | Generic/radial basis functions | Sparse/tissue dowels + extra |
| Muller | [25,55] | H | Single/specific | Face/skull | Generic/radial basis functions | Sparse/tissue dowels |
| Subsol | [36] | H | Single/specific | Face/skull | Generic/radial basis functions | Dense/crest-lines |
| Tu | [56,19] | H | Multiple/specific | Face/skull | Generic/radial basis functions | Dense/range image |
| Turner | [57] | H | Multiple/specific | Face | Generic/radial basis functions | Dense/crest-lines |
| Paysan | [20] | H | Multiple/generic | face/skull | Face-specific/PCA | Dense/feature points |

a final stage, the reconstructed facial shape can be additionally textured (given a skin colour and being pigmented) and visualized (f) in order to generate images for further distribution and recognition.

The purpose of this work is to give an exhaustive and critical review of methods that have been proposed for computer-based CFR so far. A quasi chronological list of the techniques is given in Table 1. The remainder of this paper is structured according to the generalised conceptual framework depicted in Fig. 1. Each section clarifies a component within the framework in more depth and specific choices are compared and discussed. Subsequently, we address the need for validation to increase the practical relevance of CFR methods in crime-scene investigations. Finally, we conclude this review by suggesting future directions.

## 2. Anthropological examination

The skull, which has a morphometric individuality as distinctive as a fingerprint [8], is the basic source of information for any craniofacial reconstruction. In the first instance, an anthropological examination (Fig. 1(a)) is performed in order to determine a set of skull properties including age, gender, ancestry and stature [9]. Sometimes it is even possible to estimate the body mass index (BMI) based on remaining soft-tissue layers on the skull or additional evidence found at the crime-scene, for example clothes. Computer assistance for estimating ancestry and gender is given by the software package FORDISC 2.0 [10,11] which has recently been upgraded to FORDISC 3.0 [12]. Although no completely automatic computer-aided method supporting such examinations exists to date, it is likely that automated skull classification procedures will be developed in the same way facial archetypes describing a various cohort of people are being developed today [13].

## 3. Unknown skull digitization

A digitized version of the skull is required in order to translate the skull shape into a machine-readable format for further processing, depiction and visualization. This is comparable with a cast of the skull for manual reconstruction techniques in order not to destroy the original skull and, therefore, possible evidence. Additionally, an uncovered copy for reference of original conditions is kept in this way.

Pioneering work on computerized 3D craniofacial reconstruction was first done by Vanezis [14]. In their work and in Refs. [6,15–17] the skull is digitized using a laser scanning system. Thanks to recent advances in medical imaging technology, computer tomography (CT) scanners have become a practical alternative for acquiring a digital copy of the skull. All computerized reconstruction techniques today (<5 years) use CT scanners to digitize the skull.

Both laser-based and CT scanners have their limitations and shortcomings. CT scanners are sensitive to amalgam dental restorations resulting in heavy streak artefacts in the images. Although laser scanning is a general technique for scanning the outer-surface of 3D objects, the skull surface is very complex to reconstruct based on laser-line projections. More importantly both scanners have a limited scanning resolution, such that very small details of the skull are not acquired or copied. Error is introduced during data acquisition which must be taken into account. A virtual copy is never an exact copy of the skull specimen!

## 4. Craniofacial model

An essential step in the computerized reconstruction framework is the definition of a craniofacial model (Fig. 1(c)). A CFM codes for the knowledge about human facial shapes and their relationship to the underlying skull as learned from a representative reference database of exemplar subjects. It contains the a-priori knowledge required to tackle the CFR problem and as such is the equivalent to the human artist or expert. The major difference however is that the human artist has an implicit awareness or intuition, besides explicit anatomical and artistic knowledge to perform a manual reconstruction resulting into subjective reconstruction results. A CFM encodes only explicit knowledge and contains three components: (1) a craniofacial template (CFT) being the reference to start from (facial knowledge), (2) craniofacial information (CFI) of the template containing the knowledge relating faces to skulls (anatomical knowledge), and (3) a craniofacial deformation (CFD) describing the class of constrained transformations for fitting or adjusting the CFT to a given skull specimen (sculpting knowledge).

### *4.1. Craniofacial template*

A craniofacial *template* (CFT) is the reference facial knowledge or head to start from. Different types of templates are used in different methods and are listed in Table 1. Templates can either represent a holistic (denoted by H, in Table 1), complete view of the face or can represent the face as a collection of partial features separately (denoted by P, in Table 1) like the nose, mouth and ears. Single or multiple CFT's can be used. In the single template setup, the knowledge of only one reference face is used and this can either be a generic/average or a specific individual (similar to the target skull in terms of age, gender, ancestry and skull dimensions) drawn from a database. In a multiple template setup, two approaches are observed as well. The first or "specific" approach generates a reconstruction per specific reference head in a database, resulting in multiple reconstructions of the unknown skull. A final result is generated by combining all the reconstructions into a single reconstruction. The second or "generic" approach combines the knowledge of multiple reference heads beforehand and then makes a single reconstruction based on that combined knowledge.

By selecting an appropriate CFT the reconstruction can be more or less tailored to the properties of the skull as obtained from the anthropological examination. The authors call this tailoring process *property normalization*. In a pre-reconstruction property normalization mode, the CFM is normalized to the skull properties before a CFR is made. This is the preferred mode, since the use of a CFM with properties that differ too much from the target skull, could make the reconstruction too difficult, if not impossible. In a post-reconstruction property normalization mode, only the reconstructed results are normalized to the estimated properties. This mode of operation is interesting when a property of the reconstruction needs to be altered from its value at the time of death to generate, for example, a younger version of the victim when he/she could have been missing for several years prior to his/her death.

A typical pre-reconstruction normalization approach is to select one or a set of reference heads from a database, the properties of which are similar to the ones of the skull. This is often done when using a single specific CFT. However, an extended database containing enough samples for every possible sub-population as such is required and is labour intensive to acquire. Alternatively, one can try to learn and model geometrical facial variations originating from attribute differences between faces in a database in order to simulate age, corpulence, ancestry and gender changes. The advantage is that under-sampled sub-populations in a database can still be represented by the interpolating nature of the attribute learning process. A linear statistical interpolation of attribute differences is for example used in [18,19] in a post-reconstruction mode and in Refs. [20,21] in a pre-reconstruction mode. A linear geometrical interpolation between two reconstructions with different skull properties is used to generate intermediate reconstruction results in Ref. [17].

If inappropriate templates are chosen, *model bias* can occur. Model bias is the leaking through of specific facial feature details, originating from the CFT, into the reconstruction. Using only a single generic (for example an average face) facial template or a subject-specific facial template, the potential to produce model-biased reconstructions is high, which is illustrated in Fig. 2. Indeed, when using a subject-specific template (Fig. 2(c)), based on similarity in ancestry, gender and age, unwanted facial features of the template remain visible in the final reconstruction (areas indicated by ellipses in Fig. 2 (d)). Using a generic face template (Fig. 2(a)), on the other hand, results in a reconstruction (Fig. 2(b)) that is too smooth and non-specific. In order to reduce the model bias it is better to work with multiple reference heads. Considering the human artist as being the homologue CFM for manual reconstruction techniques then it is logical to work with multiple templates. The facial knowledge and awareness of the artist is based on seeing and observing many faces during his or her life. An artist knowing only the geometry of his/her own face will make reconstructions resembling him/herself. The goal is to create a computerized craniofacial model keeping objectivity and incorporating the same amount of knowledge as a human artist. This can only be done based on a database of many and diverse faces.

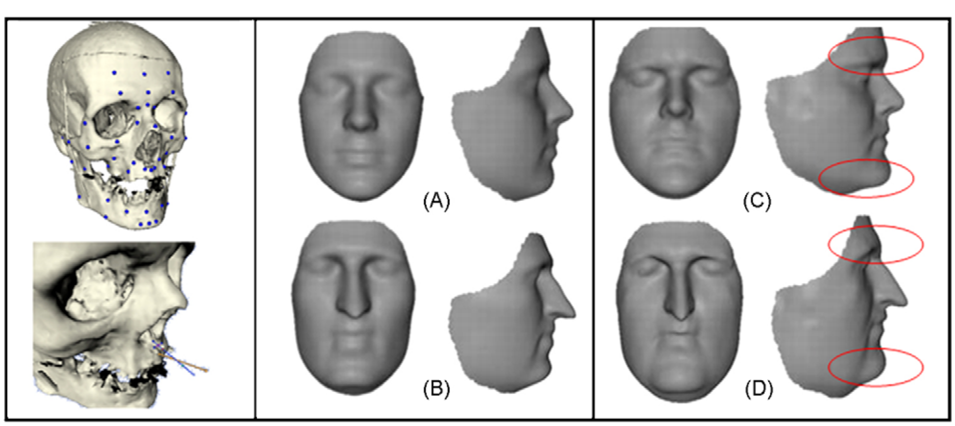


**Fig. 2.** Illustration of model bias. Two reconstructions (B and D) made of the same skull, represented as 52 skull landmarks and an estimate of the nose tip, using a single generic (A) and specific (C) CFT in combination with a generic deformation.

### 4.2. Craniofacial information

The craniofacial information (CFI) pertains to the explicit knowledge contained in the CFM relating faces to underlying skulls. This knowledge can consist of facial surfaces, tissue thickness, skull surfaces and/or facial muscles. All of the techniques incorporate knowledge about the facial surface. Quite a few techniques incorporate the skull surface besides the facial surface as well. A single generic CFT consisting of the outer facial surface and 24 facial muscles was built by [22], using graphics modelling techniques. This gives the possibility to animate the final reconstruction based on muscle movements. In Claes et al. (listed in Table 1) the facial surface knowledge is combined with soft-tissue thickness measured at 52 anatomical landmarks according to [23,24].

The choice of CFI is dependent on the type of scanning equipment used to scan subjects for building the CFM. The major advantage of using a CT scanner to build up such a database is the possibility to have reference skull surface information combined with, possibly spatially dense, associated tissue depth measurements. A disadvantage however, is the level of irradiation absorbed by the subject during CT scanning, limiting the reference database to patient data and incomplete head scans or deceased subject data. Furthermore, CT images are acquired of subjects in a horizontal, supine position. As a result, due to gravitational forces, facial shapes extracted from CT images will differ from the typical facial shape as viewed in a standing upright position. Recently, cone-beam CT scanners have been developed and are being used in medical practice in which the subject can be scanned in an upright position. However the signal to noise ratio in such scanners is lower than traditional CT scanners resulting in noisy 2D CT slices, making it harder to extract the skull surface accurately.

An alternative to CT scanners is the use of MRI scanners [20,25], which are considered not to be harmful. Again dense soft-tissue depth measurements can be acquired, including differentiation between different types of soft-tissue (muscle, fat). However, the same remark concerning the difference in facial outlook between supine and upright position of the subject during scanning holds for MRI scanners. Furthermore, the link between the soft-tissue measurements of a subject and the underlying skull is hard to establish because of the poor hard-tissue visualization in MRI. A third choice of scanning material is the use of laser-based or photogrammetric-based scanners. These scanners give the possibility to scan a person in an upright position, without being harmful. Both types of scanners are limited to scan the outer facial surface, such that additional measuring technology (ultrasound, e.g.) is required to measure tissue-depths. Because of the manual labour involved measuring the tissue-depths, the number of measurements is limited to a sparse (much $<$100) instead of a dense (much more than 100) set of anatomical landmarks on the face. An interesting and novel strategy is observed in [20]. In this work the three types of acquisition scanners are combined to obtain the best result for each CFI source: CT scanners are used to scan dry skull specimens and surface scanners are used to acquire facial surfaces from living subjects. Both these databases are used to encode for the skull and face shape information, respectively. A third but limited MRI database is used to learn the underlying skull-face shape relationship.

### 4.3. Craniofacial deformation

The craniofacial deformation (CFD) stipulates how the CFT is allowed to be deformed or transformed. The reported transformation models that are applied to the templates in order to geometrically align them with the target skull are very diverse. A first class of rigid transformations apply only a translation and rotation to manipulate the CFT. Affine transformations incorporate, besides rotation and translation, also scale and skew to deform the facial template. Rigid or affine transformations are used by all techniques in order to bring both the skull and the template into the same coordinate system. Starting from this rough alignment, local changes are needed in order to adapt the CFT exactly to the skull specimen by making use of non-rigid or non-affine deformations.

The majority of methods listed in Table 1 make use of *generic* non-rigid deformations, which are mathematically well defined and easy to use. The advantage of using generic deformations is that they are applicable to a wide range of objects and that no training phase by the computer is necessary. However care has to be taken by the operator when using generic deformations, because no knowledge of facial geometry and/or anatomy is incorporated. They are just smooth (softly evolving) and can deform a face into an awkward looking face when not used carefully. To illustrate this we applied an exaggerated displacement to the tip of the nose of the face in Fig. 3 (left). Subsequently the face was deformed based on this displacement making use of a generic interpolating deformation (Fig. 3 (middle)). The resulting face has a bigger, but very pointy Pinocchio-like nose, which is unrealistic and implausible according to human anatomy. No problem arises when the differences between the CFT and unknown skull are small. However, when these differences are relatively large, the required deformation will be more pronounced, which can result in unrealistic, caricature-like or implausible facial reconstructions.

The use of a *face-specific* instead of a generic non-rigid deformation model was first proposed by [26] and more used

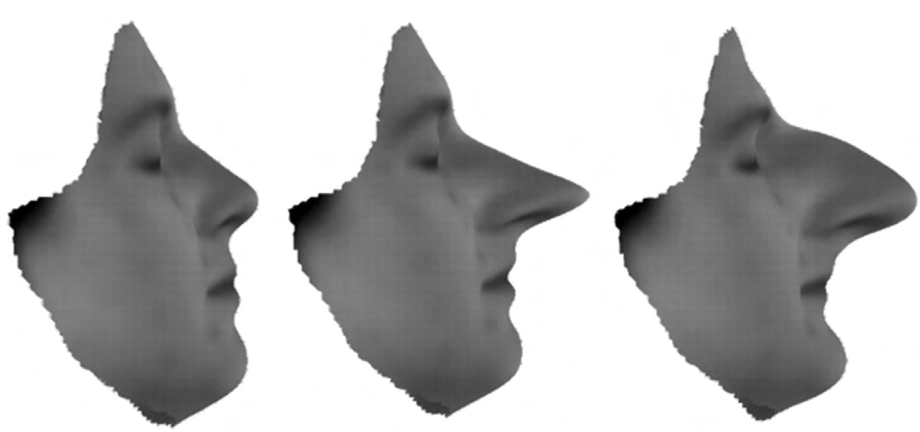

**Fig. 3.** Nose tip manipulation of a face (left) with a generic TPS based deformation (middle) and a face-specific statistical PCA based deformation (right).

since. The CFT can be considered as an elastic mask the elasticity of which is defined by the statistically allowed correlated variation or covariance of facial surfaces in a database. By changing the mask between the statistically determined boundaries, the deformation of the mask is restricted to take place in a face-specific way only. Generating a face-specific CFD typically includes a learning phase or a statistical analysis of a facial database. The advantage compared to generic deformations is that faces can be deformed in a face-specific manner within statistical boundaries, guaranteeing the facial plausibility based on a facial probability density function. To show the difference we deformed the face in Fig. 3 (left) based on the same nose tip displacement making use of a statistical interpolating deformation extracted from a PCA facial model resulting in the face of Fig. 3 (right). The final nose is anatomically more acceptable than the one based on the generic transformation. The disadvantage is that face-specific deformations learned from a database are entirely dependent on the samples in the database. Having a small database or a database with low inter-subject variance generates a small and too restrictive a set of deformation possibilities, so that faces a-typical to the database are hard to reconstruct.

## 5. Target skull representation

The fourth component in the workflow is the target skull representation (TSR) (Fig. 1(d)), which is related to the choice of craniofacial model. A skull can be represented or parameterized in different ways depending on the type of relationship between soft- and hard-tissues or CFI incorporated in the CFM. The skull representation for manual reconstruction techniques is a physical copy of the skull surface combined with dowels at specific anatomical or cranio-metric landmarks whose lengths are equal to average tissue-depths according to the anthropological examination results.

A number of computer-based methods adapt the manual reconstruction TSR by interactively positioning virtual dowels at a sparse set of anatomical landmarks on a virtual copy of the skull whose lengths equal tabulated average tissue-depths (last column Table 1). Some [6,27] expand the number of virtual dowels in between the manually placed dowels at mathematically calculated intermediate points. This virtual dowel representation is typically used in combination with a CFT consisting of a face surface, without skull surface or tissue depth information. The end-points of the virtual dowels represent estimates of landmarks on the face surface, which are typically indicated on the CFT as well. Alternatively, some methods [14,28–30] use a simulated 'tissue growth' algorithm starting from the virtual dowel representation to create an initial featureless mask of the face lacking eyes, ears, nose and mouth. The tissue thickness distributions known at the landmarks are grown starting from the skull surface by interpolating the thickness values for points on the skull surface. This kind of representation can be used in combination with facial models consisting of separate facial features. Something similar is done by [6], but instead of growing tissue, they model the muscles onto the skull after which the facial features and skin are added. In the early work of Claes et al. [18,26,31–34] a sparse set of anatomical landmarks indicated manually on the skull is used as well, but no thickness values are set out. Instead soft-tissue thickness are incorporated into the craniofacial model instead of the skull representation in order to exploit the influence of tissue thickness on facial geometry and vice versa. The authors refer to these target skull representations based on or starting from manually indicated cranio-metric or anatomical skull landmarks as *sparse cranio-metric skull representations*.

Having a CFT with facial and skull surface information, a spatially *dense skull representation* becomes an alternative. A first possibility is to represent the skull with a set of control or feature points which can be determined automatically and which can have a denser distribution than the sparse cranio-metric representations discussed in the previous paragraph. In the most extreme scenario, every point on a discrete digital representation of the skull surface is used, but in practice a subset of points is defined. A second possibility is the use of points on crest-lines as in [35]. These lines follow the salient lines of the skull surface like the mandible, the orbits, the cheekbones or the temples [36]. A third approach is to convert the 3D skull into a 2.5D range image representation using cylindrical mapping, which is a conversion of Cartesian coordinates into cylindrical coordinates.

A signed distance transform (sDT) skull representation is a completely different representation from the previous two categories and was first used in Ref. [37]. A signed distance transform (sDT) of the skull represents for each point in 3D the shortest Euclidian distance to the skull surface, zero on the surface, positive inside and negative outside. This *implicit skull representation* is a dense, almost continuous, representation and does not only code the original skull surface, but, at the same time codes an infinite set of surfaces inside and outside the skull at certain iso-distances from the skull, which are smoothed versions of the original surface.

## 6. Model to skull registration

The fifth component in the CFR framework is the registration, also called fitting or matching, which is the process of finding and applying the geometrical relationship or transformation between the CFM and the target skull. Using a particular TSR and a compatible CFM, a similarity measure is defined, which expresses the closeness-of-fit of the CFT to the skull. The CFD model is combined with the similarity measure into an objective function. During registration a set of deformation parameters is searched for, optimizing the objective function, by increasing the similarity measure within the range of possible transformations as coded by the CFD. Once these parameters are known, the CFT can finally be deformed/warped/morphed/adapted towards the target skull specimen to generate an estimate of the unknown facial geometry.

An important issue concerning the registration of the CFM towards the target skull is the presence of small errors or noise and gross errors or outliers within the skull data. Besides the fact that a virtual copy is never an exact copy of the skull specimen, additional errors are introduced during TSR build up. Making a registration robust against small errors is achieved by incorporating a regularization model into the objective function, restricting the deformation. Instead of exactly interpolating or obeying the TSR an approximation is allowed, resulting in smoother (generic) or more facial plausible (face-specific) deformations. Outliers, however are gross errors compared to the noise level present in the majority of the data constituting the skull representation and they severely influence the objective function and therefore the final transformation parameters. Increasing the regularization to deal with outliers makes the deformation too restrictive such that the model template is not allowed to change. It is better that outliers are detected and either removed or their influence on the deformation parameter estimation is to be reduced.

## 7. Texturing and visualization

Generating a good approximation of the geometry of the face belonging to the unknown skull is the most important objective of a CFR technique, but in order to generate a life-like appearance, texturing (applying skin colour and pigmentation) the reconstruction might be required. Manual reconstructions can be refined by the artist painting directly onto the clay model.

A few current computerized reconstruction techniques apply texturing in a final step of the workflow after the geometry of the reconstruction has been created. 3D modelling software can be used to virtually paint the eyes and mouth, e.g. onto the 3D surface of the reconstruction. This is also useful for creating particular details like scars or birthmarks when they are known to be present. Another possibility is to use texture mapping as in [6,36], which is a process akin to applying wallpaper to a flat surface. Besides texturing, a 2D sketch of the 3D reconstruction can be generated to make the final image appear more life-like [6,36].

The final textured reconstruction result can now be visualized with proper 3D rendering software. The advantage is that both the skull and the facial outcome can be rendered together, while adjusting a transparency parameter in order to examine the face-skull relationship. This kind of visualization makes it interesting to evaluate the reconstruction and to correct possible errors.

Texturing the reconstruction is not without warning, because it can trigger an incorrect recognition. Errors introduced at this stage can be very confusing thereby thwarting the identification. Applying the texture map of a certain living subject onto the facial geometry of a different person will trigger the recognition towards the former person. It is not advised to use a texture map from a particular individual, introducing unwanted fine detail. Instead an average texture map should be created and used to render the 3D reconstruction. Average texture maps, belonging to different sub-populations are to be created in the same way a CFM for different sub-populations is necessary. Alternatively, Refs. [21,38] incorporate texture information besides skull, face and tissue thickness information into a CFM based on multiple faces. This gives the possibility to generate more, but not too specific texture maps (compared to averaged texture maps) according to the geometry of the face, because the relationship between texture and geometry is learned.

## 8. Validation

A final, but important issue in the design of a computerized reconstruction technique is the need for validation. From a practical point of view, a developed method can work adequately, but it is of no use in real-life investigation situations until properly validated. A proper validation framework will hopefully substantiate on a scientific basis the added value of reconstruction methods during criminal investigations. A database of skulls with known facial outlooks is required and validation can be based on a leave-one-out cross-validation scenario. Here every skull in the database is removed in turn, and used as a test case. The resulting facial skin surface of the reconstruction technique can then be compared with the actual skin surface of the test case. The actual skin surface is the golden standard or ground truth of the validation setup enabling evaluations of the reconstruction result.

In a first instance a quantitative error evaluation can be performed by observing local surface differences. Comparing the two surfaces in this quantitative way is interesting for evaluating the reconstruction performance in terms of accuracy and provides a spatial map of the difficulty of each facial region to be reconstructed.

The final goal of CFR is not reconstruction accuracy, but rather recognition or identification success. A recognition test consists of comparing the CFR result with a database of candidates including the ground truth or the actual person. The goal is to retrieve the ground truth from the database. In a computer-based recognition setup this can be accomplished automatically using facial measures of similarity, which is currently an active research topic [39]. A more realistic, human subjective, identification process can be simulated by generating face-pool tests. Given an image of the CFR and a set of possible candidate images extracted from the database, a human observer is asked to indicate the face from the face-pool most similar to the given CFR. Although these face-pool tests are interesting to perform, it is difficult to generate realistic face-pool tests that reflect real-life human subjective recognition situations.

## 9. Conclusion

Forensic facial reconstruction aims at estimating the facial outlook associated to an unknown skull specimen for victim identification. All facial reconstruction techniques are based on the assumed relationship between the soft-tissue envelope and the underlying skull substrate. Manual reconstruction methods consist of physically modelling a face on a skull replica and require a lot of anatomical and artistic expertise resulting in subjective and time consuming reconstructions with widely variable results.

Computer-based methods are essentially a virtual mimicking of manual reconstruction techniques. Observing computer-based techniques today, we can define a general conceptual framework involving six compartments. The essential part is the CFM which codes for the a-priori knowledge about facial shape and its link to the skull specimen to tackle the CFR problem and which is influenced by the anthropological examination. Subsequently, this model is deformed towards a virtual copy of the skull based on a proper skull representation during the registration phase. Finally, the CFR result can be textured and rendered in order to generate images for further distribution and recognition purposes. Besides the issues concerning craniofacial reconstruction in general, a number of choices have to be made and a number of implementation issues have to be dealt with while designing a computerized CFR technique.

The ultimate CFM retains objectivity and incorporates the same amount of knowledge as a human artist. This can only be achieved by learning from a large and diverse facial reference database. In the future, it is important to collect as much craniofacial data as possible for different populations of ancestry, age, gender and BMI. The visual and life-like quality of computer-based CFR results is dependent on the quality of the samples in the reference database. If the facial samples in the database look artificial so will the CFR. Observing the progress in computer science and graphics and the improvement of medical imaging technologies it is likely that craniofacial data will be acquired more accurately in the future. Cone-beam CT is already a nice example enabling the measurement of skull and facial data in an upright position over a larger population because of the lower radiation dose involved during scanning compared with traditional CT scanners.

Craniofacial reconstruction balances between the worlds of Art and Science. Through the efforts of many people around the world and the progress in computer science the emphasis has shifted towards science to improve the practical relevance of craniofacial reconstructions within crime-scene investigations and criminal convictions. The evidential value of craniofacial reconstructions can largely be improved, when combined with appropriate facial recognition and identification techniques, both of which are currently active research topics.

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