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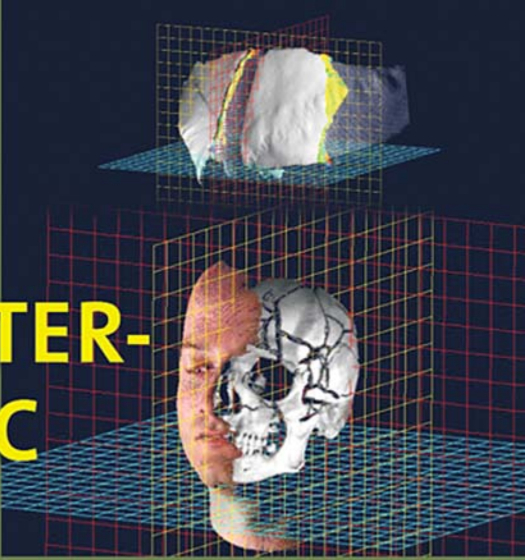

COMPUTER-GRAPHIC FACIAL RECONSTRUCTION

John G. Clement • Murray K. Marks

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FOREWORD

> It is the common wonder of all men, how among so many millions of faces, there should be none alike
>
> Thomas Browne, *Religio Medici*

The Roman philosopher Cicero said that "everything is in the face", and truly the human face is a complex, multifunctional part of our anatomy which tells the world, who we are and what we are feeling both emotionally and physically, as well as performing a number of essential physiological functions. We all have to live with our own face and with how others perceive us through its appearance. It can effect our self esteem and if we are unhappy with it we may try to alter it.

Its physical appearance and its perception by others act together powerfully to set us a real challenge in identifying an individual. This is particularly so when we try to reconstruct a face from a skull of unknown provenance. We start with the not insignificant difficulty of trying to achieve a recognition from an acquaintance of the deceased, when we have no idea who the person was to begin with or how they were remembered during life – were they happy and smiling, sad or angry? Did they have a condition which in some way characterized their facial appearance – we know that chronic pain or severe mental disorders such as schizophrenia can significantly alter facial affect in a person. Nevertheless, despite these obstacles, identifying an individual from their facial appearance remains a fascinating challenge for us worthy of serious academic study and development.

I am also mindful that facial identification, in this day and age, is an important tool to be considered both as a primary and secondary characteristic of identity, especially with the need to identify victims of conflicts around the globe that are found in mass graves and also those who have perished from apparently ever increasing natural mass disasters. There has never at any time been a problem of such magnitude needing to be resolved, and the application of different facial identification techniques may in many instances be of significant assistance.

I am delighted that John Clement and Murray Marks have assembled a text covering all the important elements of the field and with such a distinguished group of contributors, thus bringing this complex subject into the 21st century.

Together with all the high tech electronic advances which are indeed an essential cornerstone to important developments in the field, the authors are always mindful of the basic principles that underpin good science and high quality work. They remind us that there is no substitute for knowing how to accurately assess the anthropology and morphology of the face and the psychological parameters which inform our understanding of how we recognize each other. It is gratifying to see therefore that the need for the continuing use of traditional techniques is recognized.

Those of us involved in facial identification through reconstruction, should always be mindful of what is meant by “a successful reconstruction”. It is not just about whether the new face is recognized. Indeed, there are many factors which can act together to make recognition difficult, if not impossible. Hence the most physically accurate reconstruction may be deemed a “failure”. Conversely, some of the crudest attempts at reconstruction may succeed, even though the final reconstructed image does not resemble the identified person. This may be the case if the population is small and well defined with only a small number of known missing persons.

In spite of these inherent difficulties, it is essential that we always strive through scientific endeavour to improve the accuracy of the reconstructed face to achieve a good “likeness” with the person during life. I am delighted to see that this text is aiming precisely to achieve just that.

Peter Vanezis
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PREFACE

This book grew out of the FBI's 2000 International Association for Craniofacial Identification meeting, held in Washington, DC. The editors agreed to cooperate on a project that would gather the research results presented there. Four years later, as this book goes to press, research in the field of computer-graphic facial reconstruction and related areas has progressed considerably, as the variety of contributions included here testifies.

The volume is organized in four sections that discuss the current state of forensic reconstructive facial anatomy, conceptual modeling of computer-based reconstruction and their practical applications, psychological perception of facial recognition, and practical applications of facial morphometric comparisons for proof of identity.

Clement and Marks introduce the scope of the work in Chapter 1 by underscoring the anatomical and anthropological issues requiring attention by those striving to develop and employ modern computer-based methods to augment, improve, or supplant the more traditional methods for restoring a likeness upon skeletal remains in a legal or medical context.

Chapter 2, by Quatrehomme and Subsol, covers the classical approach to facial reconstruction, setting up the historical context for the material that follows.

Taylor and Craig in Chapter 3 describe the pre-reconstructive techniques necessary for the anatomical and anthropological interpretation of the skull. They demonstrate a traditional clay-based reconstruction method that provides the baseline for computer enhancement by a police artist and a comparative reference for other recent advances described in other chapters.

In Chapter 4 Thomas's "3D quantification of facial shape" critically emphasizes the need for landmark definitions and how to discern biological distance between skulls or faces or the morphological differences between reconstructions. This chapter stresses measurement and underscores the necessity in selecting the most appropriate method for the specific research question posed.

Subsol describes in Chapter 5 an automated system for 3D facial reconstruction using feature-based registration of a reference head and provides practical examples that promise to make this reconstruction process faster, more flexible, and less subjective.

Stephan and co-workers in Chapter 6 describe "average" 2D computer-generated human facial morphology and how information gleaned from these approximations should relax reliance upon the subjective information routinely used in many forensic reconstructions/approximations.

Vargas and his co-author Sucar describe in Chapter 7 their ongoing research that applies Bayesian "artificial intelligence" networks and computer graphics to forensics and anthropometry of the head and face. Their system attempts to predict facial features from skeletal. This technique is also highly relevant to corrective plastic surgery.

Tu and co-workers detail in Chapter 8 a computer graphic morphing technique using principal components analysis for generating a 3D model of a head/face from clinical CT scans of flesh depth data. This statistical treatment allows appreciation for the inherent soft tissue variation from subject to subject.

Subke describes the application of CAD/CAM engineering tools in Chapter 9 to reconstruct fragmented skulls by rearticulating images of the scanned fragments in an electronic environment. This provides an entry point for other programs predicting shape and form of overlaying facial tissues.

Davy and co-workers describe in Chapter 10 a computer-based method that faithfully emulates manual forensic sculpting. It emphasizes that such reconstructions can be attained more easily than using craft-based techniques with options for deconstruction, backtracking, and then reconstruction, while saving previous versions. Their methods aim to provide the most reliable, expeditious, and accurate reconstructions as possible without all the steps currently used in clay modeling.

In Chapter 11 Stephan and co-workers explore the recognition limits of 2D facial approximations constructed using averages. Recognition tests, based upon warping average facial color and texture on the exact face shape of specific individuals resulted in low success rates. These conditions provided observers with a more accurate representation of the individual than was possible to infer from the skull and such recognition rates for traditional clay-based reconstructions were much lower.

In Chapter 12 Kusnoto and co-workers have developed a non-invasive, economical and reliable method for measuring facial soft tissue thickness using 3D finite-element modeling from photographic and radiographic data using radio-opaque markers situated on anatomical landmarks.

Senn and Brumit describe in Chapter 13 a computer-aided dental identification method for use in a forensic setting. This system attempts to move from unverifiable subjective observations to more objective techniques for establishing identity from orofacial characteristics.

In Chapter 14 Rakover explores two methodologies in memory research entitled "explanation-testing" and "reconstruction" which critiques face recognition research and anatomical reconstruction of appearance in a forensic context that incorporate cognitive and computational models applied to facial perception.

Hill in Chapter 15 uses laser scans of faces to address perception issues. This chapter specifically describes how topography and the role of shape can be separated from the effects of other cues used in recognition. Important findings emphasize the role of the average face and movement in discriminating identity.

Shaweesh and co-workers use comparative non-contact surface measurements of young Japanese and Australian adults in Chapter 16 to create average 3D faces. Different measurement methods are illustrated and electronic hybrids with differing proportions from each ethnic group are created that could form the basis for threshold testing in series recognition experiments.

Kuratate in Chapter 17 describes the creation of perceptibly accurate 3D talking head animations from only profile and frontal photographs. This is achieved by transferring face motion from one subject to another and by extracting a small set of feature points common to both photographs and using a small set of principal components to build the facial image on which movements are displayed.

Yoshino describes in Chapter 18 a Japanese system for the morphological comparison between 3D facial scans and potential 2D image matches obtained from surveillance videos during commission of a crime. Comparison of facial outlines and anatomical landmarks are both employed and threshold values for positive identification are established.

In Chapter 19 Yoshino further develops the system described in Chapter 18 as a new retrieval system for a 3D facial image database. The system automatically adjusts orientation of all 3D images in a database for comparison with the 2D image of the suspect. It then explores the closeness of fit between the two images using graph matching.

As this summary of the contents demonstrates, this book offers a snapshot of the current state of the field. We hope that it will serve as a stimulus to further research and discussion of the rich complexities of facial reconstruction in all its facets.

JOHN G. CLEMENT
MURRAY K. MARKS
October 2004

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In addition to thanking all the contributors for their patience and fortitude during the gestation of this book, I should like to acknowledge the contributions of David Thomas, Sherie Blackwell and Diana Zeppieri, all of the Oral Anatomy, Medicine and Surgery Unit in the School of Dental Science at the University of Melbourne, who made extraordinary additional and unacknowledged efforts to see this work come to fruition.

J.G.C.

I would like to thank the contributors for so eloquently putting their research interests into words and images. I would also like to thank Academic Press/Elsevier, especially Nick Fallon, who originally allowed the notion of a volume on this topic to materialize, Mark Listewnik and Pam Chester for incredible patience and tolerance and Renata Corbani for systematically tidying up the loose ends.

M.K.M.

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AUTOMATIC 3D FACIAL RECONSTRUCTION BY FEATURE-BASED REGISTRATION OF A REFERENCE HEAD

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5.1 INTRODUCTION

As emphasized by Bramble *et al.* (2001), "two and three-dimensional computer-based reconstruction systems have been developed to make the reconstruction process faster, more flexible and to remove some of the subjectivity and inconsistencies associated with the traditional approaches (illustrative identikit and 3D clay based reconstruction)". We can attempt to classify the 3D computer-based methods that have been presented in the last fifteen years into the three following categories.

MORPHOMETRY-BASED METHODS

The user chooses some sites on the skull surface where he defines the facial thickness. A facial surface is then adjusted (or "warped") to fit with the selected sites by applying some 3D transformations. The main difficulty is in determining a class of transformations that are both complex and regular enough to deform precisely and consistently the face surface. Vanezis *et al.* (1989), who made one of the first attempts to use a 3D computer-graphic method, applied transformations that are nonuniform scalings. Since then, more complex transformations such as bilinear interpolation (Plasencia 1999), spline functions (Archer *et al.* 1998, Vignal 1999), radial basis functions (Vanezis *et al.* 2000), and hierarchical volume deformation (Petrick 2000) have been introduced.

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Computer-Graphic Facial Reconstruction
John G. Clement and Murray K. Marks, Editors

MORPHOLOGY-BASED METHODS

The user sets up the morphology of the face by including the muscles and the fat, before ending the reconstruction by putting on the skin layer. Wilhelms and Van Gelder (1997) presented computer-graphics algorithms to model the bones, muscles, and underlying skin. Kähler *et al.* (2003) fitted a precise reference anatomical model of the head on the unidentified skull by using the correspondences between some skull and skin landmarks. A similar procedure was also developed to simulate or plan facial surgery by Koch *et al.* (1996).

In fact, these two classes of methods combine an automatization and an extension of traditional reconstruction processes that are described by Quatrehomme and Subsol (2005). The first one is easier to implement as it does not require any anatomical model; rather it relies on data—some tens of landmarks and the corresponding facial thicknesses—that are very sparse.

REGISTRATION-BASED METHODS

This class of methods requires first to design a reference head model, consisting of a skull and a face model that can be extracted from 3D images acquired by computer tomography (Shaham *et al.* 2000) or 3D laser scanning (Tyrrell *et al.* 1997). The reference skull is then registered with the model of the unknown skull in order to compute a 3D deformation. This deformation can then be applied to the reference face in order to infer the unknown face (see Figure 5.1). In Nelson and Michael's (1998) paper, some structures called "discs" that define the 3D deformation are manually placed on key features around the unknown and the reference skulls. Seibert (1997) used simulated

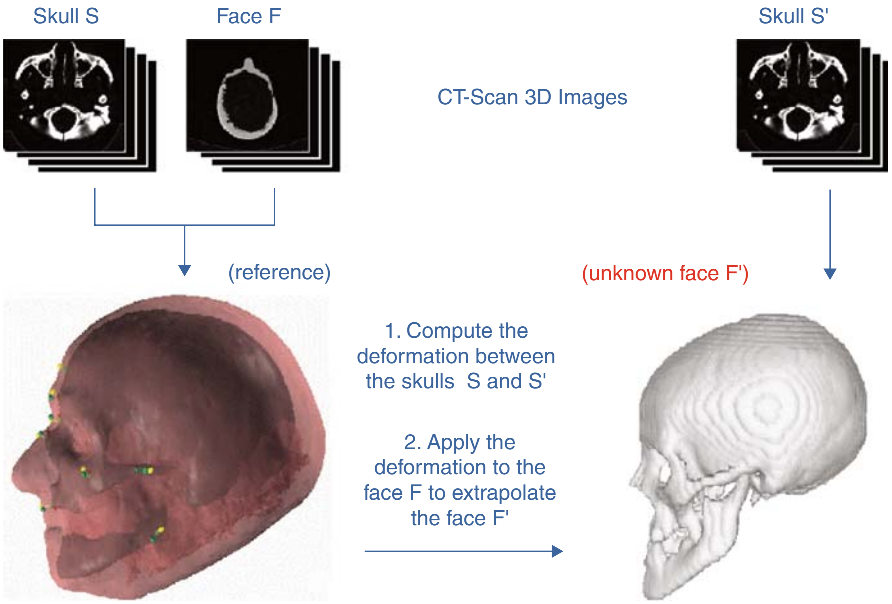

Figure 5.1

In registration-based methods, the reference and the unidentified skulls are registered and the resulting 3D deformation is applied to the reference face to infer the unknown face.

annealing to support a manual identification of corresponding features. The method of Attardi *et al.* (1999) is in two steps: some anthropological points are manually identified on the two skulls and define a first deformation that allows them to track and register new feature points in order to obtain a refined deformation. Jones (2001) proposes an algorithm based on intensity correlation between the two 3D images of the skulls to extract the feature points automatically. Tu *et al.* (2004) transform the 3D skull model into a 2.5D representation by using cylindrical coordinates. This allows the performance of a 2D registration algorithm that is based on the intensity.

Notice that the different classes of method can be also mixed. For example, Jones (2001) uses the registration result to map the facial thickness of all the points of the reference head on the unidentified skull in order to define the underlying face.

The registration-based methods appear to us as the most promising as they do not require any anthropological measurements or complex anatomical knowledge and can be based on the whole surface data of the skull and the face. Moreover, a lot of progress has been made in 3D image processing in recent years (see e.g., Ayache 2003) and many registration algorithms have been developed and tested. In the next section, we will describe the method we have investigated for several years (Quatrehomme *et al.* 1997). We will then present some results before discussing some difficulties raised by this class of methods.

5.2 DESCRIPTION OF THE METHOD

5.2.1 DATA ACQUISITION

THE ACQUISITION PROCESS

Computer-tomographic (CT) scanning of the head of a cadaver may lead to many problems. For ethical reasons, it becomes quite impossible to use a regular medical CT scanner that is used for living persons. Moreover, some technical problems can occur, for example, caused by the presence of metallic material in teeth (Spoor *et al.* 2000). A solution can be to take a cast of the face and to digitize it separately from the dry skull (Quatrehomme *et al.* 1997).

The skull and the face cast are then placed into the CT device (see Figure 5.2) which gives, in a few minutes, a series of several tens of digital images representing the successive slices of the anatomical structure. These images are, in general, of a resolution of 512 by 512 pixels which are coded in several thousands of gray levels. They are then “stacked” in order to build up a three-dimensional image. CT scanners that are routinely used in medical radiology have a resolution of one millimeter, whereas special industrial microscanners can reach up to a resolution of 100 microns (Thompson and Ilerhaus 1998).

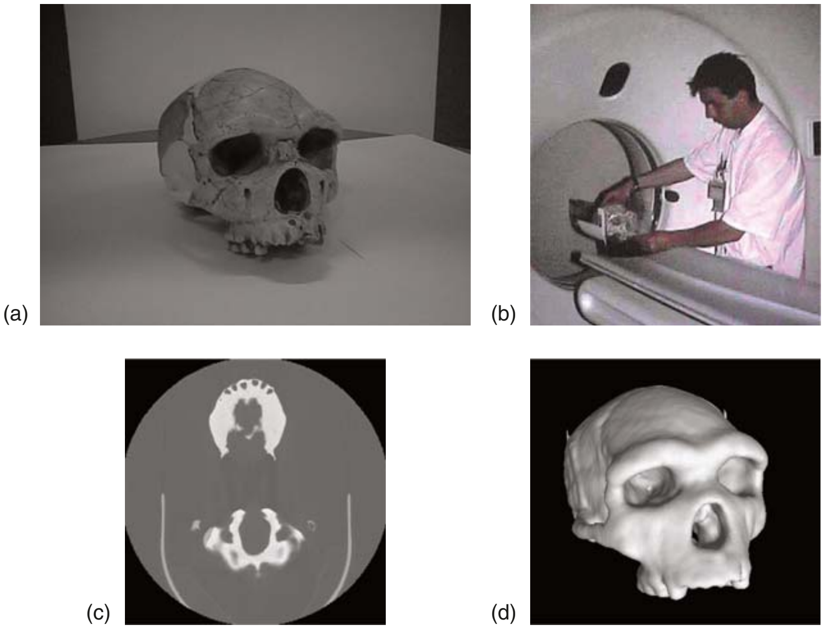

Figure 5.2

Obtaining a 3D representation of the head. The anatomical structure (or its cast) (a) is placed in the CT scanner (b). We obtain then a series of several tens of digital images of 512 by 512 pixels in gray levels that correspond to slices (c). It is then possible to "stack" the slices, extract the surface of the anatomical structure, and visualize it in 3D on a computer screen (d).

Some 3D image-processing algorithms developed for medical imaging or computer-assisted design (CAD) are applied to extract the surface of the structure from the 3D image and to display it, from any point of view, on the screen of a computer.

THE REFERENCE HEAD

As reference-head data, we used the CT scan of the cast of the face and of the dry skull of a man who died in his seventies (see Figure 5.3). The 3D images consist in 62 slices with a thickness of 3 mm, composed of 512 by 512 pixels of 0.6 by 0.6 mm. The face and the skull were aligned manually by fitting some anatomical landmarks—a difficulty being that the opening angle of the mandible must be exactly the same on the cadaver as on the skeletonized skull, and a special device had to be developed. For this reason, in the following experiment number 2, we have "deleted" the mandible in order to focus only on the upper part.

EXPERIMENT 1: UNKNOWN CONTEMPORARY SKULL

We applied the same procedure as described for experiment 2 (see Figure 5.4).

EXPERIMENT 2: PREHISTORIC SKULL OF THE MAN OF TAUTAVEL

In the second experiment, we use a CT scan of a cast of the reconstruction of the skull of an ante-Neandertalian, known as the "man of Tautavel", estimated

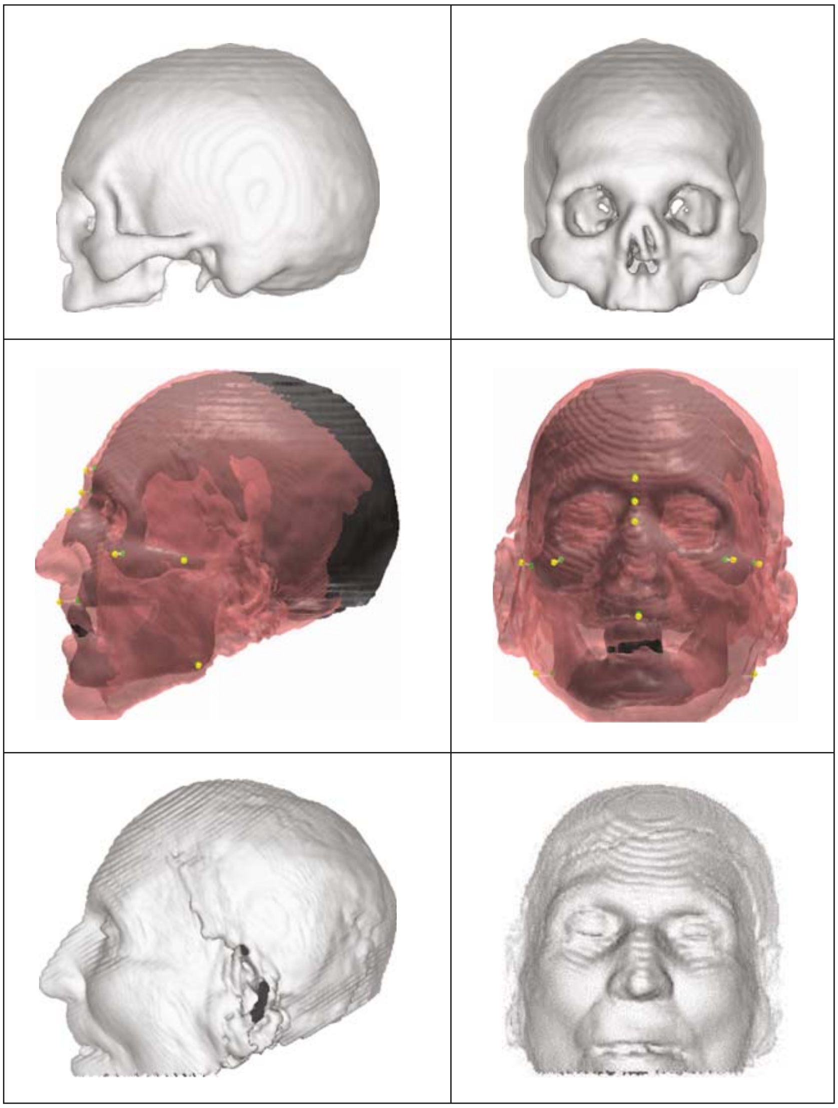

Figure 5.3 The reference head. The images of the skull (top) and of the face cast (bottom) have been manually aligned by using some anatomical landmarks (middle).

to be 450 000 years old (see Figure 5.5). The prehistoric reconstitution is based on the face (Arago XXI) and on the right parietal (Arago XLVII) that were found in the Arago cave at Tautavel, France, in 1971, and on the left parietal being obtained by symmetry, on a mold of the Swanscombe occipital, and on the temporal bone and its symmetric of Sangiran 17 (Pithecanthropus VIII) (de Lumley *et al.* 1982). The 3D image consists of 154 slices with a thickness of 1 mm, composed of 512 by 512 pixels of 0.5 by 0.5 mm.

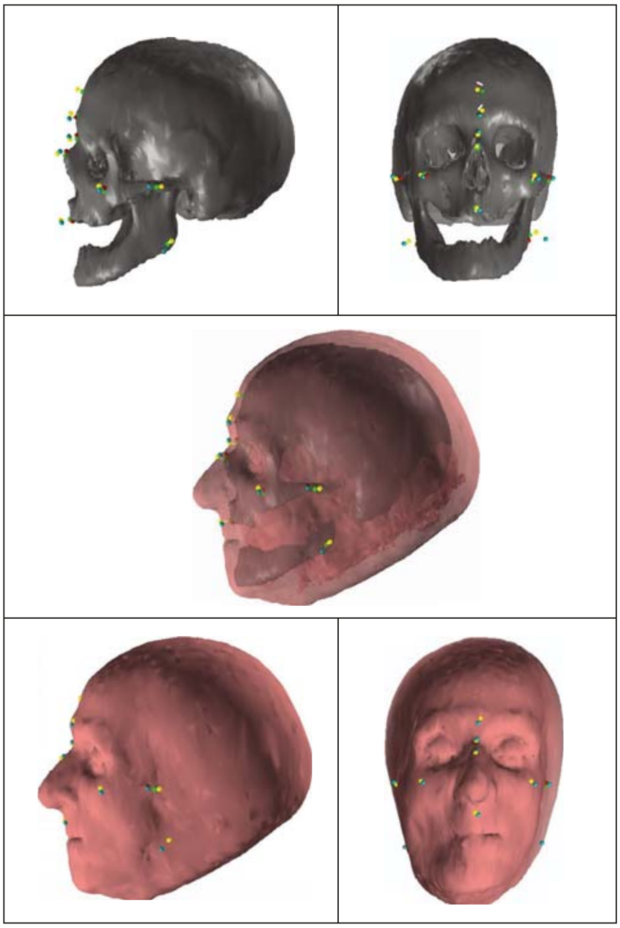

Figure 5.4 Experiment 1: as for the reference head, the images of the skull (top) and of the face cast (bottom) have been manually aligned by using some anatomical landmarks (middle).

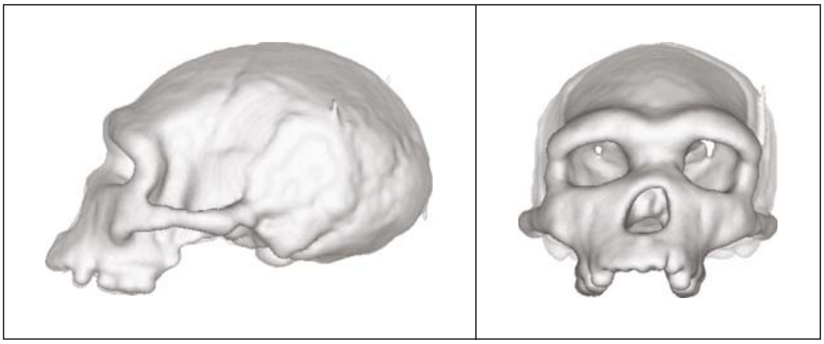

Figure 5.5 Experiment 2: the aim is to infer the prehistoric face of the Man of Tautavel from the fossil skull that is estimated to be 450 000 years old.

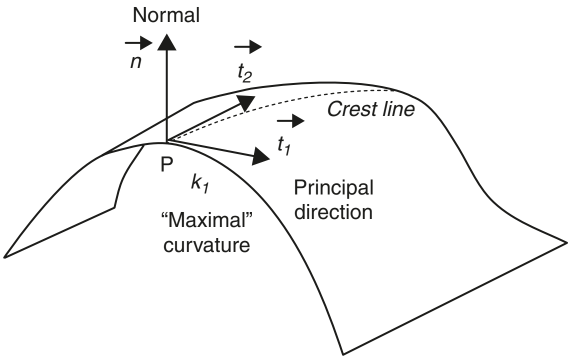

Figure 5.6

Mathematical definition of crest lines:

k_1*: maximal principal curvature in absolute value,*

t_1*: associated principal direction.*

grad $k_1 \cdot t_1 = 0 \quad \Leftrightarrow \quad P$ *is a crest point and belongs to a crest line.*

Reprinted from Medical Image Analysis (Subsol et al. *1998), with permission from Elsevier.*

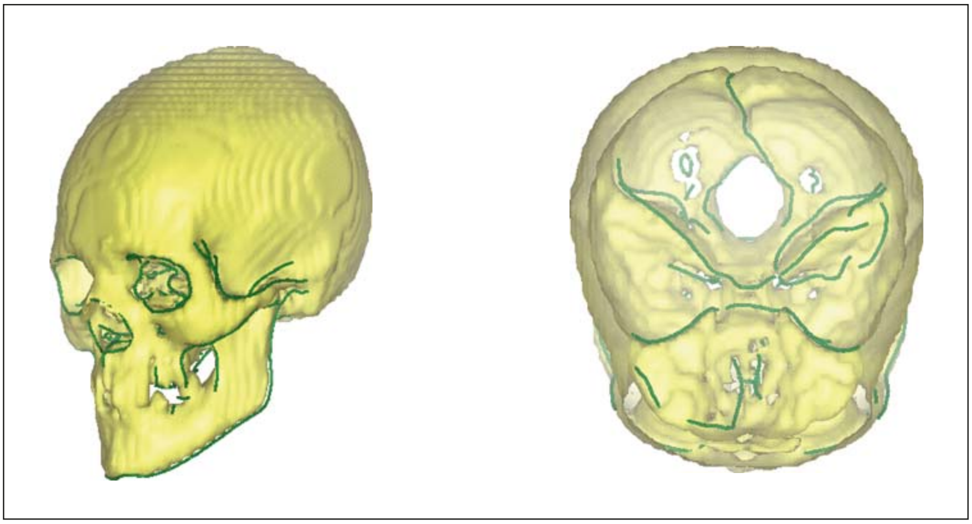

Figure 5.7 Crest lines automatically extracted in a CT scan of a skull. Notice how crest lines emphasize the mandible, the orbits, the cheekbones, or the temples and also, inside the cranium, the sphenoid and temporal bones as well as the foramen magnum. Reprinted from Medical Image Analysis (Subsol et al. *1998), with permission from Elsevier.*

5.2.2 EXTRACTION OF FEATURE POINTS AND LINES

To compute the 3D transformation, we have to find some landmarks on the surface of the skull. They must be defined by an unambiguous mathematical formula to be automatically computed and be anatomically relevant to characterize the structure. We chose "crest lines" (Thirion and Gourdon 1996) which are defined by the extrema of the principal curvature, where it has the largest absolute magnitude, along its associated principal direction (see Figure 5.6). By their definition, these lines follow the salient lines of a surface. We can check this in Figure 5.7 where the crest lines, automatically extracted in a CT scan of a skull, emphasize the mandible, the orbits, the cheekbones, or the temples and also, inside the cranium, the sphenoid and temporal bones as well as the foramen magnum.

Salient structures are also used by doctors as anatomical landmarks. For example, the crest-line definition is very close to the “ridge-line” one given by Cutting *et al.* (1993) (see Figure 5.8), which corresponds to the type II landmark in Bookstein’s typology (Bookstein 1991). In Figure 5.9, we display on the same skull the crest lines (in gray) which were automatically extracted and the ridge lines (in black) which were extracted semimanually under the supervision of an anatomist. The two sets of lines are visually very close, showing that crest lines would have a strong anatomical significance.

5.2.3 REGISTRATION OF FEATURE LINES

We extracted several hundred crest lines composed of several thousand points on the skulls and then needed to find the correspondences between these features (see Figure 5.10). Usually this is done manually by an anatomist who knows the biological homology: two features are put into correspondence if they characterize the same biological functionality. In our case, there are so many points that this becomes impossible, and we had to design an algorithm to find the correspondences automatically. This is a very well known problem in 3D image processing called “automatic registration” (Ayache 2003). We have developed a method described by Subsol *et al.* (1998) that deforms iteratively and continuously the first set of lines towards the second one in order to superimpose them. At the end of the process, each point P_i of the first set is matched with the point Q_i of the second set that is the closest, and some inconsistent

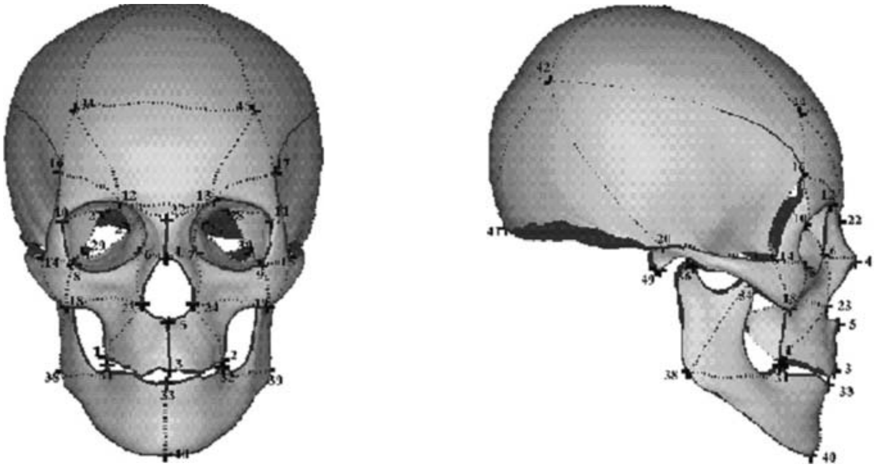

Figure 5.8 *“Ridge lines” are extracted semimanually under the supervision of an anatomist and are used for applications in craniofacial surgery and paleontology (Dean* et al. *1998). By permission of the Journal of Craniofacial Surgery.*

Figure 5.9 *Comparison of "ridge" lines and "crest" lines. The precise superimposition of crest (in red) and ridge lines (in blue) shows that crest lines would have a strong anatomical significance, even if they are based on a mathematical definition. Reprinted from Medical Image Analysis (Subsol* et al. *1998), with permission from Elsevier.*

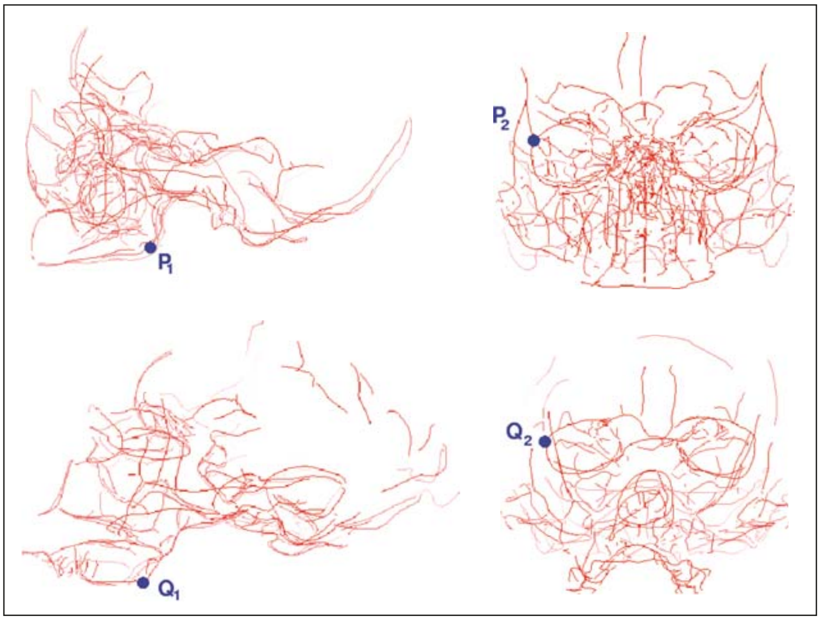

Figure 5.10

The registration problem in experiment 2. The difficulty is to find the correspondences between the features as for example, the pairings (P_1, Q_1) or (P_2, Q_2).
Top: crest lines on the reference skull (536 lines and 5,756 points).
Bottom: crest lines on the skull of the Man of Tautavel (337 lines and 5,417 points).

correspondences are discarded. In our experiments, the algorithm finds in some minutes, on a standard personal computer, around 1,500 points pairings (P_i, Q_i), located all around the inside and outside surfaces of the skull.

Thirion *et al.* (1996) checked on the data of several skulls that these registration results are consistent with those obtained by another automatic method

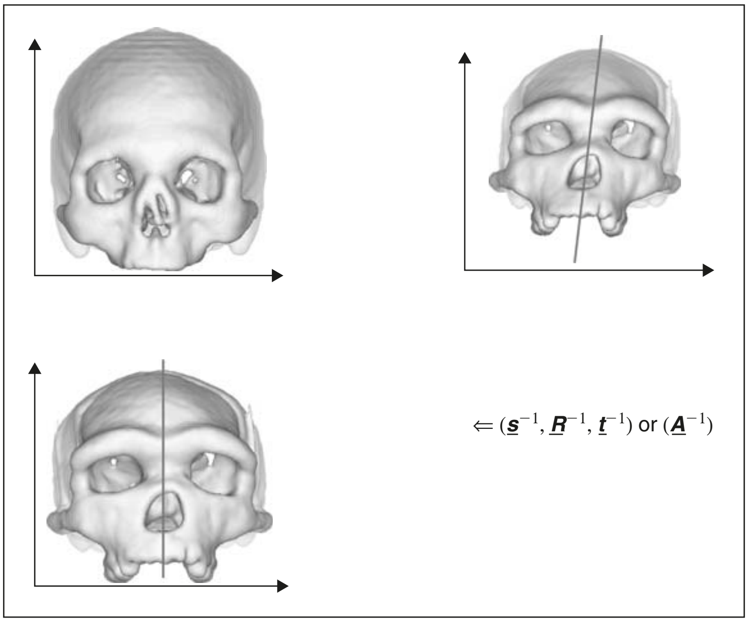

Figure 5.11 *The complex geometrical normalization in experiment 2. First, the rotation* $\underline{\boldsymbol{R}}$*, the translation* $\underline{\boldsymbol{T}}$*, and the scaling* $\underline{\boldsymbol{s}}$ *are automatically computed based on pairs of homologous points* (P_i, Q_i) *in order to align the two skulls in the same position and orientation and to compensate for the difference of global size. Moreover, we can notice that the skull of the Man of Tautavel is bent (top, right). This is due to the fact that it had lain on its side and was compressed by gravity. We have modeled this taphonomic deformation by applying an affine transformation* $\underline{\boldsymbol{A}}^{-1}$*: the two skulls are now normalized and comparable (bottom, left).*

and by a semimanual method where an anatomist supervises the detection of homologous points.

5.2.4 GEOMETRICAL NORMALIZATION

Before computing the deformation between the reference and the unknown skulls, we have to align them in the same position and orientation and to compensate for the difference of global size (see Figure 5.11). This requires the computation of the three following transformations: the rotation $\underline{\boldsymbol{R}}$, the translation $\underline{\boldsymbol{T}}$, and the scaling $\underline{\boldsymbol{s}}$. Several methods exist to compute $(\underline{\boldsymbol{s}}, \underline{\boldsymbol{R}}, \underline{\boldsymbol{t}})$ based on pairs of homologous points (P_i, Q_i), as the “Procrustes superimposition” (Boostein 1991) or the “least-square distance” minimization that leads to:

$$(\underline{s}, \ \underline{\boldsymbol{R}}, \ \underline{t}) = \text{Argmin} \ (\boldsymbol{s}, \boldsymbol{R}, \boldsymbol{t}) \sum_i \ \| \boldsymbol{s}\boldsymbol{R}P_i + \boldsymbol{t} - Q_i \|^2.$$

Sometimes, the shape of the unknown skull was altered either at the moment of the death (e.g., local deformation in the case of a traumatism or an assault) or postmortem (e.g., compression due to the weight of earth in the case of burying). It then becomes necessary to model this alteration in order to recover the original shape of the skull. Such a task is extremely difficult, as the alterations can be geometrically very complex.

Thus, in the case of experiment 2, we can notice that the skull of the Man of Tautavel is bent (see Figure 5.11, top, right). This is due to the fact that it had lain on its side and was compressed by the gravity and the weight of sediments. We have modeled this taphonomic deformation by computing an affine transformation $\underline{\boldsymbol{A}}$ between the reference and the unknown skulls. The degrees of freedom corresponding to the coefficients in the matrix representing $\underline{\boldsymbol{A}}$ allow to model the bending alteration. After applying $\underline{\boldsymbol{A}}^{-1}$, the reference and the unknown skulls are really comparable (see Figure 5.11, bottom, left).

Another way to recover the bending of the skull would be to extract automatically the midsagittal plane (Thirion *et al.* 2000) and to realign it with the vertical plane. Nevertheless, the knowledge of the in situ orientation of the fossil is indispensable, since similar deformations might be the result of many different taphonomic events (Ponce de León and Zollikofer 1999).

5.2.5 COMPUTING THE 3D TRANSFORMATION

Now, we have to compute the 3D transformation between the reference and the unknown skulls that have been both normalized. The “thin-plate spline” method (Bookstein 1991), widely used in morphometry, allows the computation of such a function that interpolates the displacements of the normalized homologous points (P'_i, Q'_i) with some mathematical properties of regularity. Nevertheless, interpolation is relevant when the matched points are totally reliable and distributed regularly (for example, a few points being located manually). In our case, these points are not totally reliable, due to possible mismatches of the registration algorithm, and are sparse in a few compact areas as they belong to lines. So, we have developed a spline approximation function that is regular enough to minimize the influence of an erroneous matched point (Subsol *et al.* 1998). The coordinate functions are then computed by a 3D tensor product of B-spline basis functions. To compute this 3D transformation $\underline{\boldsymbol{T}}$, we maximize the weighted sum of an approximation criterion (quadratic distance between $\boldsymbol{T}(P'_i)$ and Q'_i) and a regularization criterion (minimization of the sum of the second-order derivatives that correspond to the “curvature” of the function):

$$\underline{\boldsymbol{T}} = \mathrm{Argmin}_{(\boldsymbol{T})}\left(\sum_i \| \boldsymbol{T}(P'_i) - Q'_i \|^2 + \rho \iiint_V [(\partial^2 \boldsymbol{T}/\partial x^2) + (\partial^2 \boldsymbol{T}/\partial x \partial y) + \cdots]\mathrm{d}V\right).$$

The parameter ρ balances the approximation accuracy and the smoothness of the transformation.

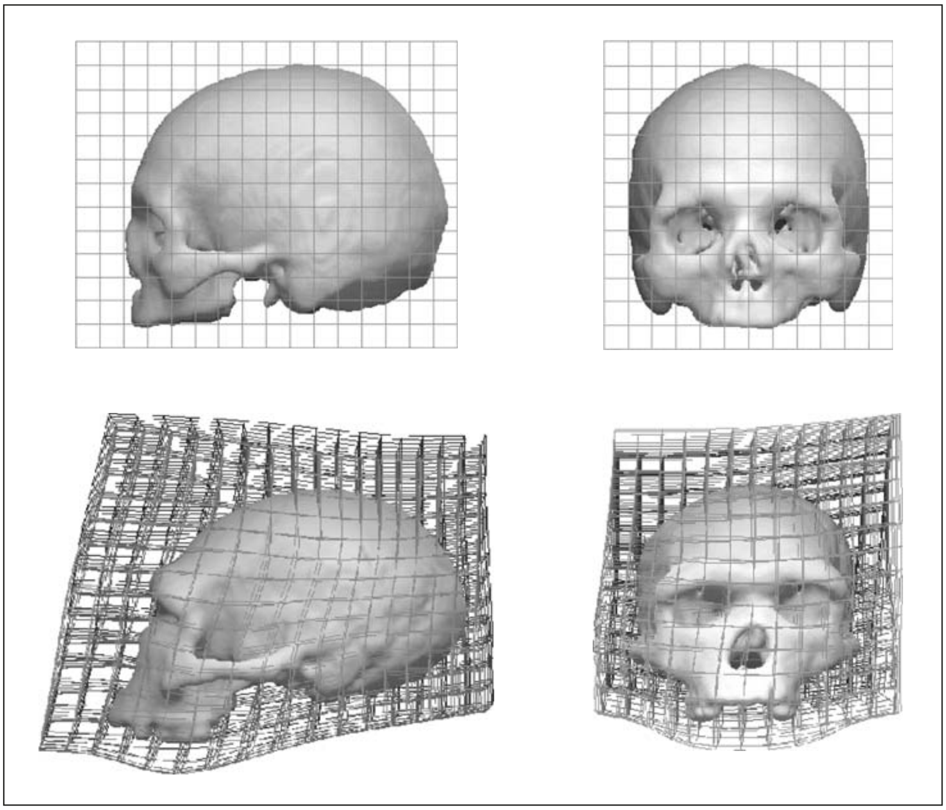

Figure 5.12 Experiment 2: the 3D transformation between the reference skull (top) and the skull of the Man of Tautavel (bottom) is automatically computed based on the registered crest lines. Notice how the deformed mesh emphasizes the main features of the skull of the Man of Tautavel: low cranium, receding forehead, and protuberant face as well as an important frontal dissymmetry due to the taphonomic deformations.

By applying $\underline{\boldsymbol{T}}$ to a 3D regular mesh, it becomes possible to display the transformation. In particular, we can notice in Figure 5.12 that the deformed mesh emphasizes the main features of the skull of the Man of Tautavel: low cranium, receding forehead, and protuberant face as well as an important frontal dissymmetry due to the taphonomic deformations (Mafart *et al.* 1999).

5.3 RESULTS AND DISCUSSION

5.3.1 THE PROBLEM OF THE VALIDATION

EXPERIMENT 1

As for all the methods of facial reconstruction, the main concern is the validity of the reconstruction result. In the first case presented, we are able to compare the automatic facial reconstruction with the real face (see Figure 5.13). Even if the reference and the actual faces have such different morphology that it is no

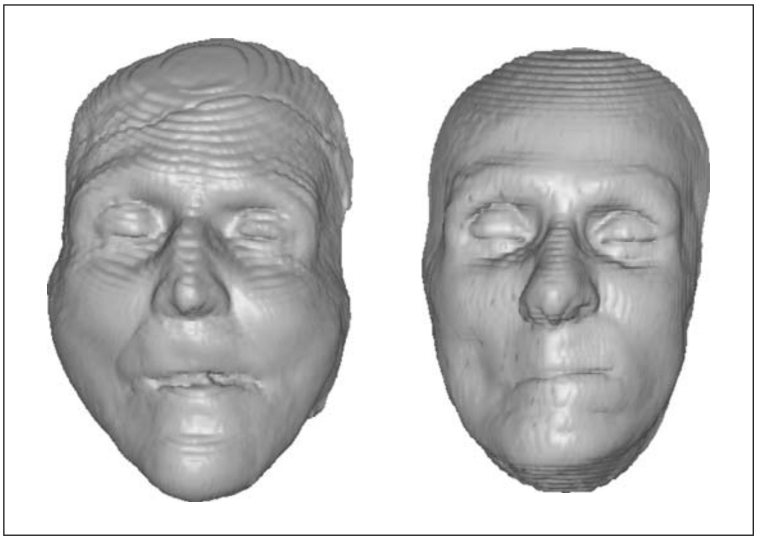

Figure 5.13

Experiment 1: comparison of the deformed reference face and of the actual "unknown" face (Quatrehomme et al. *1997). The overall proportions of the face are correctly inferred. By permission of the Journal of Forensic Sciences.*

more valid to assume the hypotheses of similarity of age or corpulence, the result looks fairly interesting. In particular, the overall proportions of the face such as the width, the interocular distance, or the eyebrow thickness are correctly inferred. The low part is less resembling, but this may be due to the difference of the opening of the mandible between the reference and the "unidentified" skulls. The soft parts as the nose or the cheeks are also not very significant.

In fact, it is very difficult to quantify the resemblances between two faces. We could compute an objective distance, based for example on the squared sum of distances between some feature points of the deformed reference and the actual faces, or even between the whole surfaces if we use dense meshes. As the distance will be never strictly equal to zero, it would require defining a threshold to decide if two faces really resemble each other. This value should be under the average distance corresponding to the intravariability of different human faces. But such a parameter, which must be computed on a very large database of representative faces, is not known yet. Moreover, some features such as hair, skin complexion, or the color of the eyes are totally absent in our virtual reconstructions, whereas they are most important for recognition. At last, when we deal with 3D models, the problem becomes much more complex: a slight shift of orientation of the representation of the reconstructed head can induce large differences in the perception of the face shape due to differences of shading or lighting.

As emphasized in (Quatrehomme and Subsol 2005), very few studies have been performed on the validation of 3D reconstruction methods on a "significant" scale, whether it is automated or not.

In conclusion, there is a strong need to define a clear and reproducible protocol to evaluate the quality of a 3D computer-assisted facial reconstruction with respect to the real face. This will allow the performance of a retrospective study to compare and validate the different methods as has been done for other image processing applications such as rigid registration (West *et al.* 1999).

EXPERIMENT 2

In the case of the Man of Tautavel, the problem is much more difficult as we do not know the actual face! Nevertheless, we can compare our reconstruction with the ones obtained with different methods (see Figure 5.14): 2D drawings and manual 3D facial reconstructions performed by an artist and by forensic medical doctors. All these methods emphasize the same morphological features of ante-Neandertalians.

The global similarity of the results are encouraging and indicate that our automatic method can give a consistent overall appearance of the face. This is all the more interesting since the reference head was not, a priori, consistent with the Man of Tautavel; the morphology is very different, as 450 000 years of human evolution separate the two men, and the Man of Tautavel is estimated to be 20–30 years old, whereas the reference man was in his seventies.

To refine the reconstruction, we could test several hypotheses on age or corpulence, based on different reference heads. This is clearly the main advantage of an entirely automatic method that allows the performance of a reconstruction in a few minutes. The problem is then to set up a significant reference head.

5.3.2 DEFINING A REFERENCE HEAD

The variation of the shape of the head is so huge that, even if we restrict a population group based on sex, corpulence, or ethnicity criteria, it is impossible to find a subject with the perfect "average" head, that could be scanned in 3D. So, very often, reference heads are taken among the models that are available to the user as the Visible Human Data Set (Koch *et al.* 1996). Nevertheless, we can describe two ways to build a significant reference head.

The first idea consists in using anthropometric or cephalometric measurements to model a virtual reference head with computer-graphic tools. DeCarlo *et al.* (1998) synthesized 3D face models of a North American Caucasian young adult male and female based on data presented by Farkas (1994).

The second idea is to infer an average model directly from a database of 3D images of different heads (see Figure 5.15). Cutting *et al.* (1993) and Subsol *et al.* (1998) extract and register line landmarks in the 3D images of a skull. The positions of the corresponding landmarks are then averaged to define the reference model. Blanz and Vetter (2004) generate 3D face models based on 200 heads of young adults (100 male and 100 female). As the images were obtained by a laser scan, it was possible to model not only the 3D geometry of the face but also the texture. The second method appears more precise, as the averaging process will take into account all data available

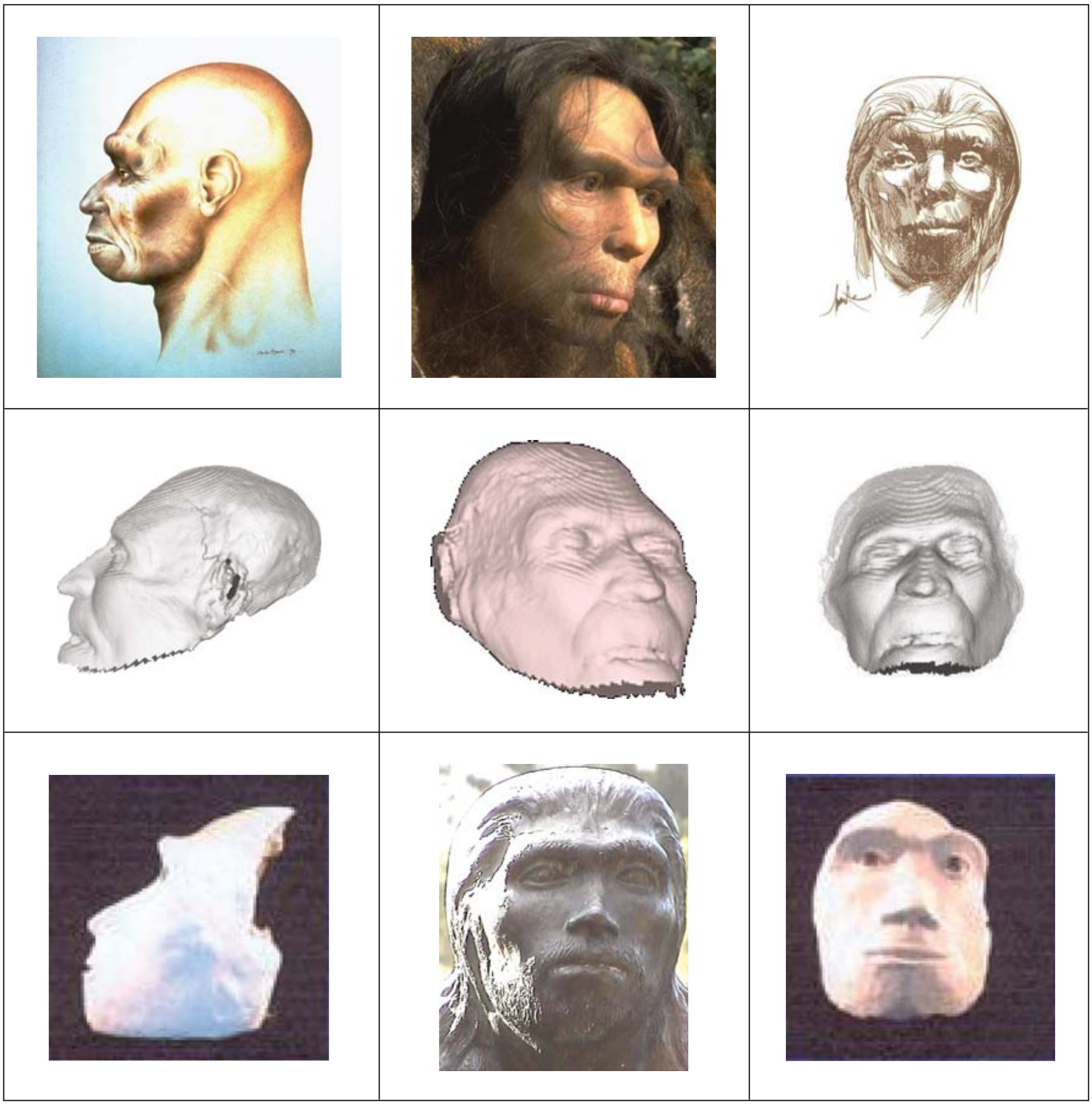

Figure 5.14 Comparison of several facial reconstruction methods.

- *Upper line, from left to right: a 2D artistic drawing by Carlos Ranzi; a 3D manual facial reconstruction performed by an artist, Elisabeth Daynes under the scientific direction of a paleontologist, Marie-Antoinette de Lumley; a 2D artistic drawing by Carlo Moretti. All these images by permission of the Centre Européen de Recherches Préhistoriques de Tautavel and its president Henry de Lumley (Tautavel, Web).*
- *Middle line: different views of our 3D computerized facial reconstruction.*
- *Bottom line:*

Left & right: a 3D manual facial reconstruction performed by forensic medical doctors (Odin et al. *2002). By permission of the authors.*

Middle: a 3D manual facial reconstruction performed by an artist, André Bordes, under the scientific direction of a paleontologist, Marie-Antoinette de Lumley. By permission of the Centre Européen de Recherches Préhistoriques de Tautavel and its president Henry de Lumley.

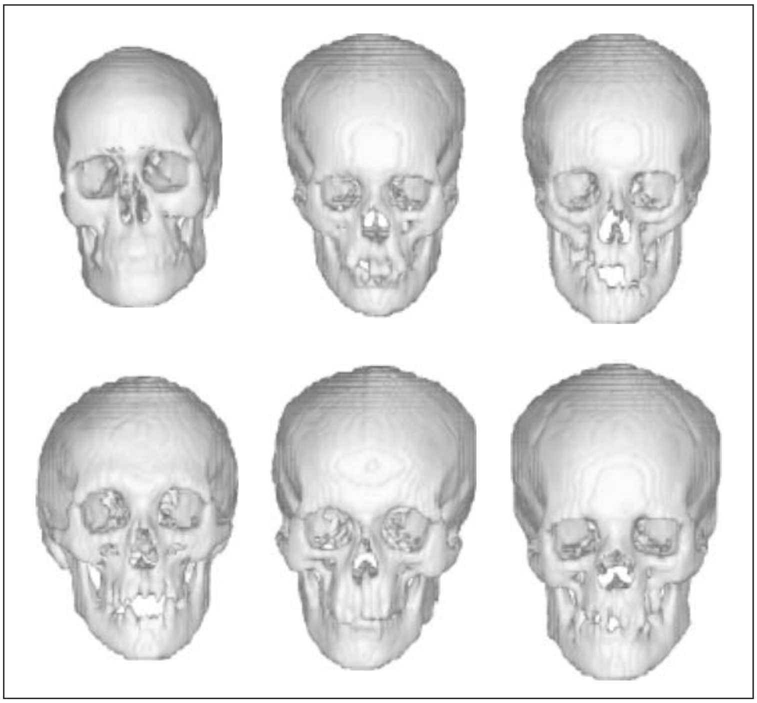

Figure 5.15

A dataset of 6 different skulls segmented from CT scans. Notice how the shapes are different. Reprinted from Medical Image Analysis (Subsol et al. *1998), with permission from Elsevier.*

in the images—up to several thousand points if the surface meshes are dense—and not only the position of some tens of anthropological landmarks. Nevertheless, no one has yet designed a complete average model of the head that includes both an average skull and a face model which are registered.

5.3.3 MODELING THE HUMAN VARIABILITY

As the presented method is automatic and fast, it is possible to test several hypotheses of reconstruction based on different criteria as age, sex, ethnicity, or corpulence. As it seems impossible to set up a database of reference heads corresponding to all the categories, a solution is to infer different heads from a reference one.

AGE

Milner *et al.* (2001) alter the 2D profile of a skull according to some cephalometric measurements and perform a manual face reconstruction to infer a face that is 50 years older. The authors caution that their work is more an exercise than a real methodology as there is no other result against which to compare it. Evison (2001) interpolates between a young and an old 3D facial reconstruction of a male, leading to intermediately aged faces. But the method is based on the hypothesis that the points of the face move linearly between the two extremes, which could be considered simplistic. Hutton *et al.* (2003) build a more complex model of facial growth based on a training set of 3D surface scans of 199 male and 201 female subjects with ages between 0 and 50. Coughlan (1997) decomposes craniofacial growth into two processes called remodeling and displacement. This model is combined with a 3D computer-based facial reconstruction method by Archer *et al.* (1998).

ETHNICITY

Dean *et al.* (1998) build average skull models using a database of skull CT-scan images of Caucasian Americans and African Americans, male and female. It allows emphasis on the anatomical differences between the ethnicities and the sexes. A range of variation that corresponds to individuals of mixed African and European ancestry could be obtained by using 3D interpolation (Evison 2001).

CORPULENCE

Archer *et al.* (1998) tune the length of the virtual “dowels” that link the face and skull models to allow the user to modify the corpulence. A 3D interpolation (Evison 2001) process can then synthesize a potential range of obesity.

EXPRESSIVITY

Kähler *et al.* (2003) build the reference head model on an anatomical basis which comprises the underlying muscles and the bone layers. Once the model is fitted to the unknown skull, it becomes possible to animate the face and obtain different expressions by setting muscle contractions. If the generic reconstruction is based on a neutral pose, it can be helpful to present several expressions for identification purposes.

5.3.4 INFERRING ILL-DEFINED FACIAL PARTS OR FEATURES

Many soft parts of the face are difficult to infer, in particular the nose, chin, eyes, lips, or ears (Quatrehomme and Subsol 2005). Kähler *et al.* (2003) express some empirical rules that are used in traditional facial reconstruction, by automatically placing vertical and horizontal guides in a frontal view. The user can then move or update some landmarks in order to refine the reconstruction. Tu *et al.* (2005) extracted a collection of eye, nose, and lip models from 3D scans of various individuals. The user can then place manually a model that will be blended on the 3D reconstruction.

More generally, a facial editing tool described by Archer *et al.* (1998) enables the user to modify locally the shape of the reconstruction. Vanezis *et al.* (2000) show how a frontal 2D view of the 3D reconstruction can be imported into a police identikit system which allows the addition of features as opened eyes, hair, or glasses.

Another way to make the reconstruction more realistic is to map a reference texture of the head on the 3D reconstruction. Attardi *et al.* (1999) and Tu *et al.* (2005) generate a cylindrical texture either from a set 2D of views or from a 2.5D laser scan of an individual whose face is assumed to resemble the face to reconstruct. The texture is then fitted and projected on the 3D reconstruction.

Notice that much research has also been performed to synthesize wrinkles (e.g., Wu *et al.* 1995) that could be added to the 3D reconstruction.

5.4 CONCLUSION

Facial reconstruction is used more and more for museum presentations (Prag and Neave 1997), but still only for human beings. With the advent of 3D computer-graphic methods, which are more flexible and require less effort and time, we can imagine performing facial reconstructions on animals. For example, the appearance of a prehistoric felid (Antón and García-Perea 1998) could be inferred from a fossil skull by using as a reference head one of a modern felid. This is completely feasible with the method presented in this chapter, as it does not depend on soft-tissue thickness measurements that we are not aware of in the case of animals. Moreover, some data are available as several fossil animals have been already CT-scanned, for example in the CT-Lab of the University of Texas at Austin, USA. Such facial reconstructions would be of the most interest for museums and could be presented either in real exhibition rooms with special graphic devices (Bimber *et al.* 2002) or on virtual Web sites (Yasuda *et al.* 2002).

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