Forensic Science International 259 (2016) 19–31

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

A regional method for craniofacial reconstruction based on coordinate adjustments and a new fusion strategy

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 27 September 2015
Accepted 8 October 2015
Available online 2 December 2015

Keywords:
Craniofacial reconstruction
Forensic identification
Region
Coordinate adjustment
PLSR
Fusion

ABSTRACT

Craniofacial reconstruction recreates a facial outlook from the cranium based on the relationship between the face and the skull to assist identification. But craniofacial structures are very complex, and this relationship is not the same in different craniofacial regions. Several regional methods have recently been proposed, these methods segmented the face and skull into regions, and the relationship of each region is then learned independently, after that, facial regions for a given skull are estimated and finally glued together to generate a face. Most of these regional methods use vertex coordinates to represent the regions, and they define a uniform coordinate system for all of the regions. Consequently, the inconsistence in the positions of regions between different individuals is not eliminated before learning the relationships between the face and skull regions, and this reduces the accuracy of the craniofacial reconstruction. In order to solve this problem, an improved regional method is proposed in this paper involving two types of coordinate adjustments. One is the global coordinate adjustment performed on the skulls and faces with the purpose to eliminate the inconsistence of position and pose of the heads; the other is the local coordinate adjustment performed on the skull and face regions with the purpose to eliminate the inconsistence of position of these regions. After these two coordinate adjustments, partial least squares regression (PLSR) is used to estimate the relationship between the face region and the skull region. In order to obtain a more accurate reconstruction, a new fusion strategy is also proposed in the paper to maintain the reconstructed feature regions when gluing the facial regions together. This is based on the observation that the feature regions usually have less reconstruction errors compared to rest of the face. The results demonstrate that the coordinate adjustments and the new fusion strategy can significantly improve the craniofacial reconstructions.

1. Introduction

Craniofacial reconstruction is a useful tool in the identification of skeletal remains when there is a lack of other forensic evidence to suggest an identity. For example, when human remains are disfigured, burnt, decomposed, or badly mutilated, craniofacial reconstruction can be a last resort to assist the investigation out of the impasse. The aim of craniofacial reconstruction is to recreate a likeness of the real face using the relationship between the soft tissues and the underlying skull, and this may then trigger memory of the relatives or friends of the victim and lead to a positive identification finally by classic techniques such as dental records, DNA-analysis, or medical records comparisons.

Traditionally, 3D craniofacial reconstruction is performed by forensic artists, who model a face from a skull by manually adding clay or plasticine onto the skull or its replica [1,2]. According to most literature, the manual methods are classified into three categories: the Russian method [3] that follows the anatomy of the head and neck, the American method [4] that relies on carefully measuring the thickness of tissues overlying the skull, and the combined method, also known as the Manchester method [5,6]. However, Stephan [7] proposed a different opinion that all of the

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http://dx.doi.org/10.1016/j.forsciint.2015.10.033
0379-0738/

methods above rely on both soft-tissue depth information and anatomical knowledge, so that the classification is inappropriate. Nevertheless, all the manual methods require anthropological and anatomical knowledge, and they depend heavily on the experience of the artists, so different artists often create extremely different results. Besides, they are often time-consuming, and only result in a single reconstruction.

With the development of computer science and medical imaging, many computer-aided methods have been proposed for craniofacial reconstruction [8–10]. Compared to the manual methods, these methods are consistent, objective and efficient. All of these methods share a same general model-based workflow summarized by Claes et al. [8]. The core of these methods lies within the craniofacial model, which contains three components: a craniofacial template (CFT), craniofacial information (CFI) and a craniofacial deformation (CFD). The CFT is the reference facial knowledge or head to start from, and it can be a specific individual chosen from a database by properties such as ancestry, gender and age of the target skull [11], or a generic face [12], or a statistic model [13,14] and so on. The CFI contains the relationship between faces and skulls, and usually this relationship can be soft-tissue depth information [15–18], facial muscles [19,20], a principle component analysis (PCA) model of heads [21,22], or a function mapping from skull shape (sometimes properties are also considered besides skull) to face shape, and this function is often obtained by regression techniques, such as latent root regression [23], support vector regression [24,25], partial least squares regression (PLSR) [26,27,16], etc. The craniofacial reconstruction for a target skull is in fact to transform the CFT to fit the target skull based on the CFI, and the transformation can be a generic non-rigid deformation [28–32], for example thin-plate spline (TPS)-based deformation, or a face-specific deformation [33,13,17], which is constrained and learned from a facial database.

Faces and skulls are very complex, and their shape variety is usually composed of global shape and local detail. Almost all of the computerized craniofacial reconstruction methods are holistic that take the whole face or skull for shape analysis. Generally for this kind of methods the global shape is emphasized but not the local detail, resulting in a general face for an unidentified skull, which is too smooth with a lack of personality and therefore not good for identification. In addition, the relationship between the face and the skull is not the same in different craniofacial regions, which is also ignored in the holistic methods. To solve these problems, some regional or partial craniofacial reconstruction methods have been proposed. Generally in these methods, skulls and faces are divided into several regions or patches, such as the nose region, mouth region, eye region and frame region. The relationship between each skull region and the corresponding face region is estimated independently. Then, for a given skull, the facial regions are reconstructed, respectively, based on the different relationships and finally stitched together to obtain a whole face. The skull and face regions can be represented in different ways, spatially sparse or dense. Landmarks [16] and distance measurements [18] are sparse ones, they are usually simple to implement but not enough to represent the rich details of regions. So, the spatially dense representation is preferred, such as the extended normal vector field [34] and vertex coordinates [27,35,22], with the latter being more commonly used. As we know, coordinates are related to the coordinate system. The methods in [27,35,22] describe that the skulls and faces are normalized by a uniform coordinate system defined by the Frankfurt plane, so that the inconsistence of head pose can be removed. However, the position and rotation of the facial features or regions are differs between individuals, and this inconsistence cannot be removed under the uniform coordinate system. Therefore, an additional local coordinate system for each skull region and its corresponding face region is required.

In addition, when stitching the facial regions together to create a full face, the existing regional methods usually glue the feature regions, i.e. eyes, nose, mouth and ears, to the frame region, whose size is much larger than the formers. Theoretically, the reconstruction for a small region will be more accurate than that of a large one, since it involves more details for the reconstruction. This is further confirmed in our practice, as shown in the results and discussion section of this paper. So, in order to maintain the reconstructions of the feature regions, a better way for fusion is to glue the frame region to the feature regions instead.

Based on the above, an improved regional method for craniofacial reconstruction is proposed in this paper with two main contributions:

(1) Two types of coordinate systems are defined, one is global, that removes the inconsistent head pose; the other is local, that removes the inconsistent positions and rotations of regions. This could calculate more accurate relationships between the face and skull regions.
(2) A new fusion strategy is proposed. By gluing the frame region to the feature regions, the advantage of regional reconstruction could be well maintained thus leading to a more accurate reconstruction.

2. Materials and methods

Fig. 1 shows the overview of our method. It includes two phases. The first phase is to learn the relationship between the face and the skull, and it consists of six steps (the rectangles colored in light gray). The first step is to reconstruct the skull and face surfaces from CT images and construct a head database. All of the heads within the database are then transformed into a uniform coordinate system, called the global coordinate system in the second step, and the dense point-to-point correspondence of different skulls (faces) is established by a 3D registration method in the third step. Afterwards, the normalized skulls and faces are segmented into seven regions in the fourth step, and local coordinate systems are defined to unify the skull regions and the corresponding face regions in the fifth step. Finally, the face and skull regions are represented by parameters through PCA, and their relationship is estimated through PLSR in the last step. The second phase is to reconstruct a face for a given skull. The skull is first transformed into the global coordinate system and normalized by the registration method. Then, it is segmented into seven regions, which will be transformed into the local coordinate systems, respectively, later. Afterwards, face regions will be created by using the relationships obtained in the first phase, and then transformed back to the global coordinate system, and finally stitched together to generate a whole face for the skull.

2.1. Database construction

We have constructed a head database from CT images, and the project has been approved by the local ethical committee. 331 patients planned for preoperative osteotomy surgery or inspection, gave informed consent for their whole head to be scanned by a clinical multi-slice CT scanner system (Siemens Sensation 16), and other information recorded such as age, height, weight and hometown was self-reported by the patients. The CT images of each subject were stored in the DICOM format with a size of approximately $512 \times 512 \times 250$. All the patients were of Mongoloid ancestry with 161 female and 170 male subjects. For female, the age distribution ranges from 18 to 75 years with an average of 41.5 years, and the BMI ranges from 17.8 to 32.9 with an average of 24.2. For male, the age distribution ranges from 20 to 70 years with