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Craniofacial reconstruction as a prediction problem using a Latent Root Regression model

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ABSTRACT

In this paper, we present a computer-assisted method for facial reconstruction. This method provides an estimation of the facial shape associated with unidentified skeletal remains. Current computer-assisted methods using a statistical framework rely on a common set of extracted points located on the bone and soft-tissue surfaces. Most of the facial reconstruction methods then consist of predicting the position of the soft-tissue surface points, when the positions of the bone surface points are known. We propose to use Latent Root Regression for prediction. The results obtained are then compared to those given by Principal Components Analysis linear models. In conjunction, we have evaluated the influence of the number of skull landmarks used. Anatomical skull landmarks are completed iteratively by points located upon geodesics which link these anatomical landmarks, thus enabling us to artificially increase the number of skull points. Facial points are obtained using a mesh-matching algorithm between a common reference mesh and individual soft-tissue surface meshes. The proposed method is validated in term of accuracy, based on a leave-one-out cross-validation test applied to a homogeneous database. Accuracy measures are obtained by computing the distance between the original face surface and its reconstruction. Finally, these results are discussed referring to current computer-assisted reconstruction facial techniques.

1. Introduction

In forensic medicine, craniofacial reconstruction refers to any process that aims to approximate the morphology of the face from the shape of the skull [1]. It is usually considered when confronted with an unrecognisable corpse and when no other identification evidence is available. This reconstruction may hopefully provide a route to a positive identification. In recent years, computer-assisted techniques have been developed following the evolution in medical imaging and computer science. As presented in the surveys in [2–4], new approaches are now available with reduced performance timeline and operator subjectivity.

Reproducing the stages of manual methods, the first machine-aided techniques fitted a skin surface mask to a set of interactively-placed virtual dowels which were on the digitised model of the remains [5–7]. Latter techniques have moved away from the manual techniques and two kinds of methods can be distinguished based on the representation of bone and soft-tissue volumes. The first techniques aim to conserve the continuous nature of the skull and soft-tissue surfaces. Estimates of the face are obtained by applying space-deformations to couples of identified bone and soft tissue surfaces, called reference surfaces. These deformations are learned between the surface of the dry skull and the surfaces of the reference skull. They can be parametric (e.g. B-splines) [8,9], implicit using variational methods [10,11] or volumetric [12,13]. Depending on the method, the final estimated face can be either the deformed face whose reference skull is the nearest to the dry skull [12,13] or a combination of all the deformed soft-tissue surfaces [9,14].

The second type of approach chooses to represent individuals using a common set of points. As the position of the corresponding points for all the individual can be summarized as variables in a table, the main idea is then to use statistics to decipher the relation between the skull and the soft-tissue. The common set of points can either be anatomical landmarks [6,15] or semi-landmarks located following a point correspondence procedure [16,18]. Semi-landmarks are defined as points that do not have anatomical meanings but that match across all the samples of a data set under a reasonable model of deformation [19]. The larger the set of points, the closer this surface representation is to a real surface.

Apart from the practical constraint of the number of anatomical landmarks that an expert can define and extract, there is no

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justification to a chosen number of points. Indeed, the information given by the position of skull anatomical landmarks is double. First, there is the geometric information given by the coordinates of the point. Then, the "anatomic" information is provided by the measuring of tissue thickness made at this point. This information is available for a limited number of points, due to the difficulties in localisation and in thickness computation. However, the geometric information given by the position of the point can be completed by automatic methods of semi-landmarks extraction. The second part of the data analysis framework consists in learning relationships between the soft-tissue variables and the bone variables. Facial reconstruction consists of predicting the positions of the soft-tissue points knowing the positions of the set of skull landmarks. In this regression problem, the skull points are entries of a regression model while the face points are the model output. Typically, a linear modelisation is used to fit this regression based on Principal Components Analysis (PCA) for example [14–16], following the work made in the statistical atlas field. However, several linear regression methods have been developed, some sharing the use of PCA. For example, latent variables regression methods such as Latent Root Regression [20,21] are designed to take the presence of variable colinearity into account, namely the positions of the skull landmarks and of the face semi-landmarks.

In this paper, we propose a facial reconstruction technique using Latent Root Regression, before comparing the results given to those obtained by a PCA model. In conjunction, we question the number of skull landmarks necessary. Basing our first experimentation on skull anatomical landmarks extracted by an expert, we will iteratively add supplementary mathematical skull semi-landmarks following the point correspondence technique described in [22], which relies on the geodesic paths between the landmarks to define new landmarks.

The paper is organised as follows. The materials and methods are presented in Section 2. Section 2.1 presents the material on which this study has been carried out. Sections 2.2 and 2.3 focus on resolving the point correspondence problem, describing the two methods used to obtain the two subject-shared description of the bone and soft-tissue surfaces. Section 3 presents the statistical methods used: the building and use of a statistical shape model and the multivariate Latent Root Regression method. Section 4 shows the results obtained by the different models and discusses the influence of the number of skull landmarks and of the statistical method chosen.

2. Materials and methods

2.1. Materials

This study was performed using whole head and skull surface meshes extracted from whole head CT scanners for a project on facial reconstruction at Paris Descartes University. The head CT-scan database of healthy people build for this project is composed of several type of data: head CT-scans, triangulated and closed surfaces covering the skull and the face, soft-tissue measurements at predefined skull landmarks [23,24]. These anatomical skull landmarks were manually located on each CT Scan according to classical methods of physical anthropology (13 midpoints and two sets of 13 lateral points). This database, and the processes performed on it, is described in detail in Tilotta et al. [24].

In the framework of this study, we focus on a group of 47 European female patients aged from 20 to 40 years. As properties such as age, gender and ancestry can be determined by anthropological examination [25], we choose to build statistical models on a homogeneous database following these criteria. In our case, the 85 subjects of the database /]*)>(.*)//tgcirxrrwere distributed according to sex and age group (20–40 years, 40–65 years) with age groups determined so as to take ageing into account. Women aged from 20 to 40 years correspond to the largest group of the database. Body weight is another factor that affects facial form [26]. In our case, none of the 47 women has a body mass index (BMI) superior to 30. 8 subjects are underweight (BMI: <19), 34 subjects correspond to a normal weight (BMI: 19–24) and 5 subjects are overweight (BMI: 14–30).

The entries of our database will consist of left or right halves of each surface. The skull and the face do not have symmetric shapes, but the relationship between these shapes does not depend on the side of the head. The plan minimising the distances to the anatomical midpoints has been chosen as an artificial boundary between the right and left part of the shapes. The next step is to extract points which correspond to the same places on the different individuals, with respect to this symmetry constraint.

2.2. Point correspondence procedure for the bone surface

The anatomical landmarks located by the expert (Fig. 1A) establish a first correspondence between the skulls. Following the scheme presented in [22], we define a set of triangular connections between these anatomical landmarks. For each pair of connected points, we can extract a geodesic between these points. Geodesics are defined to be the shortest path between points on the curved spaces of the shape surfaces (see Fig. 1B). As the shape surface between two landmarks is different from a sphere, theses geodesics are unique with high probability. At this step, a gross template of curves on the surface between the landmarks is built. We then can define new landmarks as the midpoints of each geodesic. These landmarks are used to build new geodesics as seen in Fig. 1C and a more dense triangulation is then derived. The process is iterated to form a dense geodesic triangulation with associated semi-landmarks. The obtained structures form meshes, which share the same structure for each individual, and implicitly solve the point correspondence problem. Moreover, the defined structure is symmetric: the two entries (left and right) of the database share a common substructure and set of midpoints (Fig. 1D). Due to numerical instabilities, two methods of geodesics computation on surface meshes have been used: The Surazhsky algorithm [28] and the *Fast Marching Algorithm* [29] implemented by Peyre in the Geowave library. For two iterations of this procedure, the results show three sets of skull landmarks for each individual:

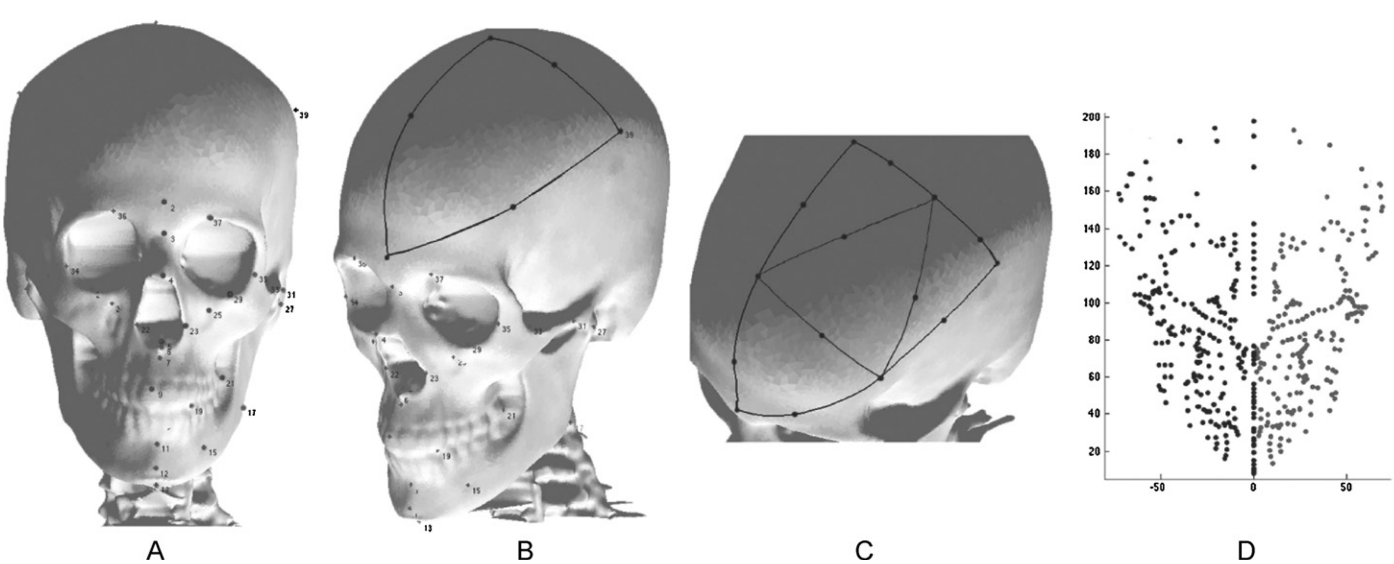

Fig. 1. Extracted landmarks and semi-landmarks for the skull [22].