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A local technique based on vectorized surfaces for craniofacial reconstruction

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ABSTRACT

In this paper, we focus on the automation of facial reconstruction. Since they consider the whole head as the object of interest, usual reconstruction techniques are global and involve a large number of parameters to be estimated. We present a local technique which aims at reaching a good trade-off between bias and variance following the paradigm of non-parametric statistics. The estimation is localized on patches delimited by surface geodesics between anatomical points of the skull. The technique relies on a continuous representation of the individual surfaces embedded in the vectorial space of extended normal vector fields. This allows to compute deformations and averages of surfaces. It consists in estimating the soft-tissue surface over patches. Using a homogeneous database described in [31], we obtain results on the chin and nasal regions with an average error below 1 mm, outperforming the global reconstruction techniques.

1. Introduction

Facial reconstruction is justified by the fact that the craniofacial substrate may, to a certain extent, be considered as a matrix supporting soft facial tissue. All facial reconstruction techniques are based on the relationship between the soft tissue morphology and the underlying skull substrate. The aim of facial reconstruction is to obtain an approximate representation of the real face to suggest a resemblance to a missing person [13,2].

Traditionally, facial reconstruction uses techniques such as drawing or sculpture. Sculpture is usually realized after one or several preprocessing steps such as (i) evaluation of the thickness of soft tissues at reference landmarks on the craniofacial block, (ii) positioning of morphological characteristics such as muscular attachments [14,19], and (iii) use of geometrical rules for localization of the eyeballs or of the tip of the nose (see [28] and references within). Facial reconstruction has evolved greatly due to the development of computer science and medical imaging (see the surveys in [6,8–10,38] and references therein). Today, the computerized reconstructions range from practitioner-led methods, which only facilitate the sculpture, to fully automated reconstructions which aim at reducing operator-related subjectivity.

We can distinguish two kinds of fully automated approaches. The first one uses a data analysis framework where each individual is represented by a same set of variables, either (landmark approach:) skull anatomical points and associated soft-tissue thicknesses [7,36], or (head model approach:) generic meshes describing the skull and face surfaces [3,17,32]. In this setting, people learn from the database the statistical relation between skull variables and soft-tissue variables so as to predict soft-tissue variables associated to a new dry skull. The second type of approaches aims at using a continuous representation of the skull and face surfaces. In this setting, the skull surfaces within the database are mapped onto a new dry skull so as to estimate the unknown face surface. This estimate is obtained applying on the faces the deformation learned on the skulls. The deformations used for mapping surfaces can be parametric (e.g. B-splines) [18,35], implicit using variational methods [23,24], or volumetric [27,26]. In landmark and head model approaches the computation of statistics like means or the data mining analysis (e.g. Principal Component Analysis) are straightforward as the data can be summarized in a table. This is unfortunately not the case for continuous surfaces as these objects are not embedded in a vectorial space.

All these approaches are global, since they consider the whole head as the object of interest. Consequently, one needs to describe

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either the generic meshes or the deformations by a large number of parameters in order to capture properly the complexity of the object to be estimated. But, statistically, it is well known that, in order to control the estimation quality, one should obtain a good trade-off between bias measuring the accuracy of the estimator and variance related to the number of estimated parameters [37]. Hence, the global approaches cannot achieve a good estimation quality, as the number of estimated parameters is too large. This is especially true as the size of the learning database is usually small. Besides, in all these approaches, the soft-tissue is recovered using an average computed over the population of a whole database (either mean soft tissue depths or mean surfaces). As a result, these non-adaptive reconstructions tend to enhance coarse and global similarities between individuals and to disregard the local variability of the facial morphology.

In this paper, we present an original technique of facial reconstruction which departs from the previous ones according to several aspects. First of all, the technique is not based on the use of a parametric approach, neither landmark nor head model. Instead, it relies on a continuous representation of the individual surfaces which makes it possible to capture their natural complexity. Second, the technique is local and thus, needs only few parameters for the reconstruction. It consists in estimating the soft-tissue surface over well-defined areas called "patches". These patches are delimited by surface geodesics linking a few predefined anatomical points in a same neighborhood of the skull. The estimation is done using the same patches available in our large database composed of whole head CT scans, extracted skull and face surfaces, and some useful anatomical and geometric information [31]. Furthermore, our estimator is constructed in a non-linear way to ensure its statistical adaptivity to individual and local disparities.

Our reconstruction technique is based on a representation of surfaces, as introduced in [33,34] using the mathematical notion of currents. This representation, which has since proved effective in many other medical applications [1,12], considers surfaces as vector fields defined on the whole space. It provides several features which are essential for the design of our facial reconstruction technique. Geometrically, the mathematical framework of currents is particularly well adapted for defining and computing distances between surfaces. The mathematical objects associated to surfaces belong to a vectorial space and therefore, can be added and multiplied by a scalar number. Thus, statistically, the average of surfaces can be defined and computed, which is fundamental for the facial reconstruction. Another major advantage of currents is that it does not require any parameterization of the surface: the surface is only represented by a cloud of points (the number of which may vary between surfaces) associated to a set of normal vectors. Mathematically, this flexibility of currents permits local manipulation of surfaces, and in the context of facial reconstruction, enables to envisage a local approach to soft tissue estimation based on dense meshes representing bone and skin surfaces.

The paper is organized as follows. The materials and the methods are presented in Section 2: the mathematical representation of the surface is introduced in Section 2.2, the construction and the registration of patches are respectively described in Sections 2.3 and 2.4. Our statistical estimation is presented in Sections 2.5 and 2.6. Section 2.7 summarizes the reconstruction technique. Section 3 is devoted to the presentation of the reconstruction results on two patches corresponding to chin and nasal regions. These results are discussed in Section 4.

2. Materials and methods

2.1. Materials

The study was carried out on a database of 47 whole head CT scans performed on European voluntary female patients, aged 20–40 years. Mathematical and computational processes were performed on the scanned images to extract the skin and bone surfaces. We also manually located about 30 anatomical points on each CT scan. This database, and the processes performed on it, are described in detail in [31].

2.2. Extended normal vector field

Here we briefly describe the mathematical model which underlies our approach. This section directly takes up ideas presented in [33] while presenting them in a somewhat more intuitive manner. We start from a given arbitrary surface S, and associate to it the set of unit and oriented normal vectors to the surface. For points $x \in S$, we will denote $\vec{S}(x)$ the corresponding normal vector. The map $x \mapsto \vec{S}(x)$ is the intrinsic normal vector field of the surface. This vector field defined on the surface S is then transformed into a vector field defined on the whole space called extended normal vector field (ENVF), as follows.

Consider the tridimensional Gaussian kernel

$$k_\sigma(r) = \frac{1}{(\sqrt{2\pi}\sigma)^3} e^{-(r^2/2\sigma^2)},$$

associated to the density of the centered Gaussian distribution with standard deviation σ in $\mathbb{R}^3$. This choice of kernel was favored because of its intuitive interpretation. We construct a so-called ENVF $\vec{S}^\sigma$ which is defined for every point x in space by

$$\vec{S}^\sigma(x) = \int_S k_\sigma(|y - x|)\vec{S}(y)\, dS(y),$$

where

- $|y - x|$ represents the Euclidean norm of vector $y - x$,
- the integral $\int_S$ is taken on the whole surface S,
- $dS(x)$ represents the infinitesimal element of surface at point y.

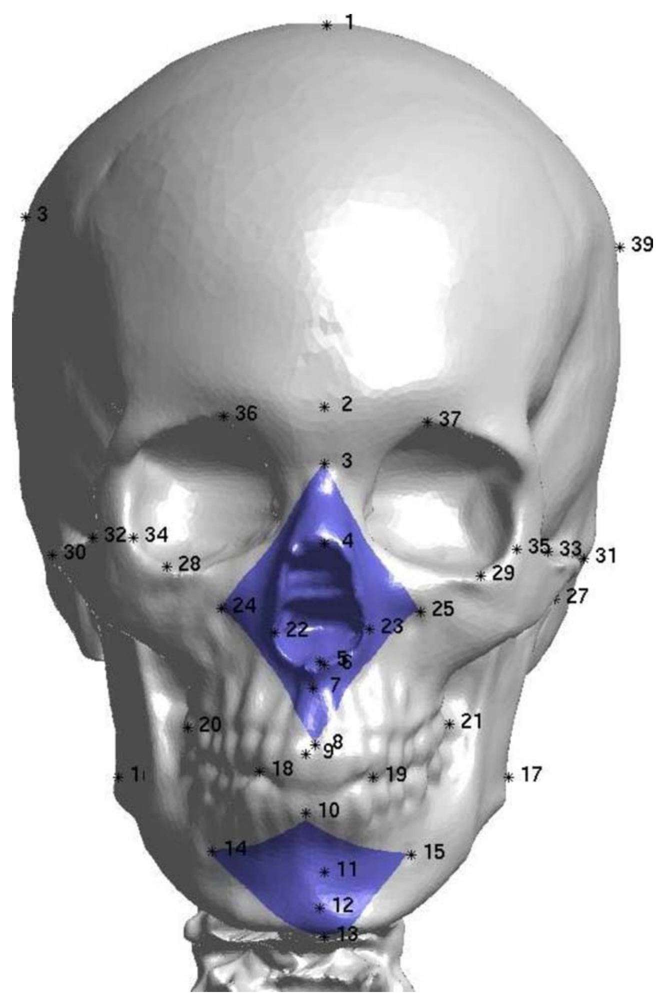

Fig. 1. Localization on the skull of the anatomical landmarks available in the database [31], and the two patches (in blue), delimited by geodesics between the selected sets of landmarks, corresponding to the chin and nasal regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)