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MANDIBULAR ASYMMETRY CHARACTERIZATION USING GENERALIZED TENSOR-BASED MORPHOMETRY

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Abstract

Quantitative assessment of facial asymmetry is crucial for successful planning of corrective surgery. We propose a tensor-based morphometry (TBM) framework to locate and quantify asymmetry using 3D CBCT images. To this end, we compute a rigid transformation between the mandible segmentation and its mirror image, which yields global rotation and translation with respect to the cranial base to guide the surgery's first stage. Next, we nonrigidly register the rigidly aligned images and use TBM methods to locally analyze the deformation field. This yields data on the location, amount and direction of "growth" (or "shrinkage") between the left and right sides. We visualize this data in a volumetric manner and via scalar and vector maps on the mandibular surface to provide the surgeon with optimal understanding of the patient's anatomy. We illustrate the feasibility and strength of our technique on 3 representative patients with a wide range of facial asymmetries.

Index Terms

Tensor-based Morphometry; mandibular asymmetry; shape analysis; orthognatic surgical planning

1. INTRODUCTION

Craniofacial deformity occurs in around 5% of the US population, and 2% of these have facial asymmetry severe enough to be disabling and stigmatizing. Facial asymmetry includes a spectrum of malformations that result from maxillary and/or mandibular hypoplasia or hyperplasia (under- or over-development of the mandible) of the affected side of the face [1, 2]. Facial asymmetry is common and often poses a challenge in craniofacial diagnosis and treatment planning. The wide variability in the etiology and the presentation of the disease makes proper assessment and quantification of the differences between the right and left sides crucial for diagnosis, treatment planning, and follow up.

We propose a new method for precisely locating mandibular asymmetry for diagnosis of facial deformities and for the planning of corrective and reconstructive procedures, based on tensor-based morphometry [3]. Deformation-based morphometry (DBM) [4] is an image analysis technique that locally assesses structural differences between an image and a common anatomical template based on the deformation field necessary to warp the image into the template's coordinate frame. This methodological framework has been used successfully in several brain morphometry applications [5, 6, 7, 8] to quantify and visualize shape differences on a voxel-by-voxel basis. Tensor-based morphometry (TBM) is an extension of DBM, where measurements are typically performed on the full deformation tensor.

The novel contribution of this paper is the adaptation of the TBM techniques for assessing asymmetry in the mandible as well as quantifying this asymmetry via ROI-based analysis. Magnitude and directionality of the asymmetry are provided in seven regions of clinical relevance.

Tensor-based morphometry has the potential to be used as a diagnosis and surgical planning aid for facial asymmetries. The proposed framework presents promising novel results and opens new research lines in the field of craniofacial corrective surgery, where quantitative morphological studies are crucial for accurate design of a surgical plan.

2. BACKGROUND

Treatment planning and assessment of the surgical correction of asymmetrical deformities is limited by reliance on 2D radiographs in the current clinical setting. The 2D radiographs conventionally used in orthodontic practice are particularly problematic when rotational or asymmetrical correction is required since surgical jaw displacements are inherently 3-dimensional [9, 10]. The use of cone-beam computed tomography (CBCT) or spiral computer tomography (CT) provides the 3D imaging data necessary to generate precise knowledge of the location and the magnitude of facial asymmetry features, which are essential for the diagnosis of facial deformities and for the planning of corrective procedures [11]. An increasing number of studies have demonstrated that computer aided surgical simulation (CASS) can predict possible surgical complications and lowers material costs while decreasing surgery duration, with comparable or better surgical outcomes. However, the ability to visualize the facial asymmetry in 3D surface models does not imply the ability to quantify and precisely locate areas of asymmetry [12, 13]. Detailed analysis of positional as well as morphological discrepancy between the affected side and the normal side in an asymmetric patient is a prerequisite for ideal treatment planning. The goal of this paper is to improve the ability to measure mandibular asymmetries for correction of facial deformities through an innovative 3D quantitative structural analysis using tensor-based morphometry.

Deformation-based morphometry (DBM) [14] quantifies the spatial relationships between anatomies of subjects, by analyzing deformation fields typically obtained through non-rigid registration of the subject images to a canonical template. The local amount of warping necessary to register the images is a rich source of information about the individual images. To this end, the deformation field is used as an index of the local differences between each anatomical structure and the template or between experimental groups. Literature reports DBM studies of the brain shape [15, 8, 16] that investigated brain changes in various disease processes as well as the normal developmental trajectory. However, little work exists regarding the detection of asymmetrical morphometry [17] and neither DBM nor TBM have been fully exploited outside of the neuroimaging field. We propose a novel frame-work that will be thus greatly beneficial to the craniofacial research community.

3. MATERIALS

In order to illustrate the potential of our methods, we use 3 pre-treatment CBCT images from the grant “Improving Treatment Outcomes for Patients with Facial Deformity using 3D Imaging”. The subjects were taken from a consecutive collected sample that sought care at our Dentofacial Deformities Program and consented to participate in the project. The inclusion criterion was clinically detectable asymmetry, defined as more than 2 mm of chin deviation or cant of the occlusal plan before the start of orthodontic treatment. Exclusion criteria were history of previous jaw surgery and need for reconstructive surgery, since graft planning was not the objective of this study. New Tom 3G CBCTs (AFP Imaging, Elmsford, NY) with the patient in supine position were obtained prior to orthodontic treatment. Manual

segmentation involved out-lining the shape of structures in each slice of the CBCT-3D images. 3D virtual models were built from a set of 300 axial slices per image, resampled at 0.5 mm isotropic resolution.

4. METHODS

The typical experimental setting for the application of TBM consists of identifying changes between groups of subjects. However, the present work is a subject-specific analysis, focusing in identifying mandibular asymmetric shape features by comparing a mandibular structure's left and right sides. Unlike many other prior studies based on a cross-sectional design, we performed a patient-specific image data analysis with a preoperative scan obtained from each subject. This scan is non-rigidly registered to its own mirror and the resulting deformation field is analyzed via TBM techniques following the work presented in [18] and [19].

4.1. Mirroring and cranial-base registration

Each preoperative scan was mirrored using an arbitrary sagittal plane. The original and the mirrored images were first rigidly registered on the cranial base (see Fig. 1). Cranial-base registration is important since it will provide information of the mandibular asymmetry relative to the face.

4.2. Surface Smoothing

The original and mirrored images are converted into 3D mandibular triangulated meshes via a marching cubes algorithm. To facilitate deformable registration, a surface inflation is performed to remove noisy artifacts from the data typically visible around the dental line. We used an iterative mean-curvature based surface evolution algorithm [20] that smoothes the surface mesh using a relaxation operator, such that the vertices are repositioned according to $V_i^{t+1} = (1 - \lambda)V_i^t + \lambda\bar{V}_i^t$ where V_i is the position of the i^{th} vertex, t is the number of iterations, $\lambda \in [0, 1]$ is a smoothing parameter, and $\bar{V}_i^t$ is the average vertex position, which is the average position of neighboring triangle centers weighted by the triangle areas. Note that the inflation has to be done in small increments to avoid introducing topological changes. The total smoothing in the data was less than half a voxel on average, thus representing the mandibular surface accurately.

4.3. Deformation fields

The smoothed original and mirrored surface are rigidly registered to obtain the translational and rotational differences in relationship to the face (Table 1). The resulting meshes are scan-converted into binary volumes and then deformably registered using a greedy fluid flow algorithm[21]. This well-known viscous fluid model accommodates large-distance, nonlinear deformations of small subregions of the target image.

4.4. Deformation Tensor Measurements

Tensor-based morphometry metrics are locally computed from the deformation fields obtained by nonrigid warping.

Determinant of the Jacobian matrix—A nonrigid deformation subjects the source image to local modifications which changes the volume of regions to adapt them to the target image. The determinant of the Jacobian ($\det(J)$) is the metric that expresses the resulting local volume change around a voxel in the source image. If $\det(J) = 1$ there is no local volume change, if $\det(J) < 1$ there is local volume decrease, and if $\det(J) > 1$ there is

local volume increase [22]. The log of the Jacobian determinant will be used in this study, since numerous studies indicate its outperformance [18].

Geodesic Anisotropy—Geodesic Anisotropy (GA) is defined as the shortest geodesic distance between the tensor and the closest isotropic tensor [18]. GA therefore measures how directionally-preferential a tensor is. Fractional anisotropy (FA) is the most commonly used metric for this purpose, but since it relies on Euclidean distances, it is not fully appropriate for positive definite symmetric manifolds. GA uses geodesic distances, which overcomes this problem. In the specific case where two tensors commute, affine invariant and Log-Euclidean metrics give identical distances between them. GA obeys this condition, as isotropic tensors are proportional to the identity matrix I , with $GA(S) = (Trace(logS - \langle logS \rangle I)^2)^{1/2}$ where S is the strain tensor and $\langle logS \rangle = Trace(logS)/3$. GA as described in [18] has a range of $[-\infty, \infty]$. We report $\tanh(GA)$ to normalize the range to $[0,1]$.

Deformation Direction Vector—Conventional scalar TBM methods are unable to present direction-specific analysis of volume changes. Recently, Rajagopalan et al. [19] designed a method to obtain the principal deformation direction from the Jacobian matrix. The main deformation direction at each voxel is computed by $J = RS$ where J is the Jacobian matrix, S is a positive definite strain tensor defined by $S = (J^T J)^{1/2}$ and $R = JS^{-1}$ is an orthogonal rotation matrix such that $R^{-1} = R^T$ and $\det R = +1$. The deformation direction vector (DDV) is computed by extracting the principal eigenvector of the strain tensor S , and rotating this by R . For visualization purposes, this vector field can be mapped into the surface reconstruction of the target image, with vectors weighed by $|det(J)|$. Additional color-coded images can be obtained by mapping this direction tensor to a RGB scalar, giving a gradient between isotropic and highly anisotropic deformation. This map is similar to the color FA maps often used in DTI visualizations (red: left-right, green: anterior-posterior, blue: inferior-superior). The intensity of the color is weighed using the log determinant of the Jacobian matrix.

5. RESULTS

Three representative cases of hyperplasia and ideopathic origin asymmetry were analyzed to illustrate the power of the proposed methodological framework.

First, we report global rotation and translation amounts in the cranial-base coordinate frame (Table 1). Since surgeons first correct for rotational and translational deviations using the face of the patient as a reference, the results in Table 1 are highly relevant in clinical settings.

Next, mean and standard deviation of the Jacobian determinant and the GA are analyzed for each one of the clinically relevant mandibular regions. The preliminary results shown in Table 2, while not used in a clinical setting yet, have been evaluated by clinicians and are considered to have great potential for orthognatic surgery planning. Both magnitude of the deformation (determinant of the Jacobian) and directionality of the deformation (GA) accurately captured the asymmetric features in the patients. The additional surface visualizations provided (Fig. 2) were especially useful for surgeons in the development of a surgical plan, as they offer more detailed shape information than the one obtained by simple visualization on 3D renderings generated from CBCT and 2D radiographs or the use of a facial plane for the assessment of occlusal cants.

6. CONCLUSIONS

This pilot study reveals the suitability of TBM to accurately detect mandibular asymmetric shape features. 3D diagnosis and treatment planning via TBM have great potential for benefiting patients and surgeons, as a complement to the current diagnostic procedures used in clinical environment. In the preliminary results shown, TBM accurately detected asymmetric features that are to be surgically corrected. Additionally, the novel visualizations via surface mapping proposed have proved to be helpful for the clinical community, illustrating the power of our methodological framework.

Since all the measurements presented are largely dependent on the deformable registration method, future work will focus on studies to evaluate the robustness of our findings with respect to the choice of registration method. We will further conduct clinical validation studies with specifically focus on pre- and post-surgery models to investigate the reliability of our diagnosis-aid tools.

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Fig. 1.

(a) Cranial base virtual surface model for a patient (white) and arbitrarily mirrored image model (purple); (b) original model and arbitrary mirror matching on the cranial base as a result of a voxel-based registration; (c) Virtual surface model (white) and registered mirrored image model (orange); (d) Close-up showing mandibular asymmetry.

Fig. 2.

Cross-sectional and surface mapping visualizations for a single subject. The red curve on all cross-sectional figures shows the outline of the mandibular surface. (a) Log-determinant of the Jacobian. Red (dark in the cross-sections) represents shrinkage and blue (bright in cross-sections) represents growth between mirror and original structures. (b) GA. Green (dark in the cross-sections) represents isotropic deformation and red (bright in cross-sections) represents anisotropic deformation. (c) DDV. The vector field is color coded (green: small, red: large) using the absolute value of the magnitude of the log-determinant of the Jacobian, while the cross-sections are color coded using the directional sphere.

Table 1

Rotation and translation disagreement in relationship with the face (after cranial base registration) in millimeters and degrees.

	Translation (x, y, z)	Rotation (x, y, z)
Case 1	(-37.65, 19.65, 2.72)	(0.04, 2.10, 14.39)
Case 2	(15.21, -2.91, 14.63)	(0.10, 8.71, 2.68)
Case 3	(17.97, -8.30, -5.03)	(0.65, 4.56, 4.30)

Summary statistics for magnitude (jacobian determinant) and the directionality ($\tanh(GA)$) of deformation. Values are shown as average (standard deviation).

Table 2

	log (det (J))			tanh (GA)		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
LeftCondyle	-1.65 (0.98)	0.28 (0.15)	-0.37 (0.35)	0.57 (0.12)	0.22 (0.08)	0.25 (0.10)
LeftRamus	-0.37 (0.35)	-0.03 (0.37)	0.1 (0.3)	0.46 (0.15)	0.25 (0.11)	0.24 (0.13)
LeftBodyMandible	-0.26 (0.32)	-0.1 (0.28)	0.1 (0.2)	0.33 (0.13)	0.28 (0.09)	0.24 (0.08)
Chin	0 (0.24)	-0.04 (0.3)	-0.05 (0.24)	0.26 (0.12)	0.31 (0.12)	0.28 (0.10)
RightCondyle	0.7 (0.55)	-0.39 (0.29)	0.23 (0.24)	0.39 (0.15)	0.28 (0.07)	0.21 (0.07)
RightRamus	0.24 (0.27)	-0.09 (0.26)	-0.21 (0.32)	0.37 (0.14)	0.26 (0.09)	0.26 (0.11)
RightBodyMandible	0.13 (0.23)	0.04 (0.33)	-0.18 (0.22)	0.22 (0.09)	0.32 (0.10)	0.25 (0.11)