A SEMIAUTOMATIC SEGMENTATION METHOD, SOLID TISSUE CLASSIFICATION AND 3D RECONSTRUCTION OF MANDIBLE FROM COMPUTED TOMOGRAPHY IMAGING FOR BIOMECHANICAL ANALYSIS

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ABSTRACT

Finite Element Analysis using geometrical 3D models obtained from medical imaging is a widely used method in the study of the mechanical properties of jawbone and dentition with important contributions in diagnosis, treatment, and outcome assessment. Numerical analysis in biomechanics seems promising yet it requires a careful reconstruction of specimens to make analysis reliable and feasible. A semi-automatic approach is described for the classification of the solid tissues of jawbone for a subsequent construction of a 3D geometrical model of mandible from CT images to perform a Finite Element mechanical analysis. Mechanical properties of jawbone in fifteen women at different stage of life were studied. Differences in displacement were found statistically significant among age groups, ANOVA test, $F=2.75$, $p=0.04$. Preliminary results differentiate biomechanical parameters of jawbone among life span in women concordant with findings in different studies using other techniques.

Index Terms— Mandible, biomechanics, active contours, finite element analysis, medical imaging, computed tomography.

1. INTRODUCTION

The study of mechanical properties of mandible is of increasing interest for researchers and clinicians [1,2] and numerical analysis is becoming important since it has been widely implemented in the study of the mechanical performance of the mandible [3, 4]. Finite Element Analysis (FEA) using geometrical models derived from 3D representations of mandible obtained from medical imaging is the preferred method [2] with important contributions in diagnosis [5], surgical/treatment planning [6,7] and outcome assessment [8]. Computer-based FEA seems to be very promising with several advantages associated [2]. Strength and strain can be obtained with relative ease using FEA, unlikely with experimental analysis[9], and many FEA software can produce mesh models automatically saving a large amount of work, although this process still requires a careful reconstruction of specimens in order to make analysis reliable and feasible [10].

A very important step in creating geometrical models for FEA is segmentation of the tissue of interest [9]. Segmentation of mandible is a complex process due to the high heterogeneity of its morphology present in the set of images, with an extremely change between slices where structures appear and disappear. Also there are three different types of solid tissues found in the jaw: cortical bone, cancellous bone and teeth. Although different studies have implemented threshold segmentation [10, 11] for tissue classification, we consider it is not the best method to differentiate cortical bone and teeth, especially regarding teeth roots, since cortical bone and teeth elements share similar attenuation coefficients or CT numbers [12].

In this paper, a semi-automatic approach is described for the classification of the solid tissues of jawbone, and for the subsequent construction of 3D geometrical models of mandible from CT images, to finally create models for FE mechanical analysis and applied in healthy women jawbones for studying variations of mechanical properties among life span.

2. MATERIALS AND METHODS

Twenty-five subjects were analyzed with an age range 21-90 years old, distributed in age groups (21-30 years old = 6 patients; 31-40 = 4 patients; 41-50 = 3 patients; 51-60 = 4 patients; 61-70 = 2 patients; 71-80 = 5 patients; 81-90 = 1 patient). CT images were obtained in a 64-slice CT scanner (Philips Brilliance, Phillips Medical Systems, Best, The Netherlands). All necessary algorithms for proper extraction of mandibular tissues were developed under MATLAB 7.6 (The Mathworks Inc., Natick, Massachusetts, USA). The mechanical analysis was performed using ANSYS (Ansys Inc., Southpointe, PA, USA). Three mechanical parameters were studied: Von Misses stress, Von Misses strain and displacement vector sum.

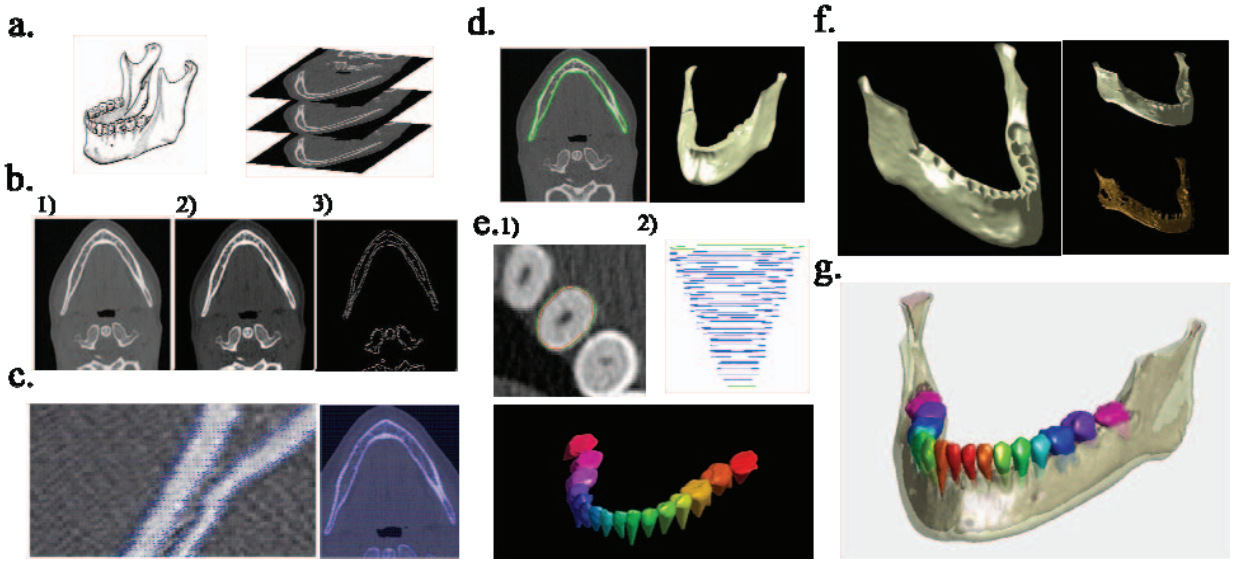


Figure 1. Workflow, *(a) Computed Tomography in vivo image acquisition of the mandible of a patient. (b) 1) Noise reduction 2) Contrast modification 3)Edge detection. (c) Calculation of external forces used in the algorithm of active contours (GVF). (d) Curve fit to the contour of the bone (active contours.); Generation of the volume corresponding to bone tissue (including dental cavities M Bone. (e) 1) Curve fit to the contour of the tooth crown as initial curve for segmentation either by active contours or Otsu's method. 2) Modeling of the tooth root by interpolating intermediate contours; generation of the volume corresponding to the teeth M Teeth. (f) 1)Logical operation to obtain the volume of bone tissue without cavities 2) classification of cortical bone and cancellous bone tissue. (g) 3D reconstruction of the resulting mask.*

2.1. Workflow

The workflow is illustrated in *Figure 1*.

As a first step in the pre-processing of images noise elimination with a Gaussian filter was implemented. Contrast change was performed for reducing gray level variance. Then an edge map was defined by Roberts method [13] previously to the Gradient Vector Flow (GVF) forces calculus [14]. For bone segmentation, an initial outline was manually drawn in one of the slices and automatically adjusted to bone's contours by active contours method. The resulting adjusted contour was used as initial contour for adjacent slices and subsequent slices were automatically segmented. A three-dimensional binary mask was finally created (*Figure 1.d right*).

Segmentation of each tooth included two steps: segmentation of crown and modeling of roots.

Segmentation of crown was based on two options and both were able if necessary, according to the case. The first option has been based on active contours method. Active contours used, as a initial contour, a curve at bottom of the crown. As in the case of bone segmentation, adjusted contour was used as initial contour for upper subsequent slices. The top of the crown was defined manually. The second option was a single threshold segmentation of the crowns from the background, based on Otsu method [15]. The contour of the bottom of the crown was used for defining a squared ROI applied to slices between the top and the bottom of the crown. This step is based in a previous method described by Al-Rawi et al. [16].

For modeling roots an interpolation of the curves was implemented. Two reference curves were defined: the adjusted contour at the bottom of the crown and a smaller circular-shape curve at bottom of the root. . The curves of the slice *i+1*, *i+2*, …, *i+j-1* were created from the information provided by reference curves using lineal interpolation (*Figure 1.e.2*). For the case where there were two or three roots, as molars, interpolation was performed for each one. Finally, it was created a three-dimensional binary matrix filling the interior regions that made up the curve of each tooth.

So far, the segmentation of bone and teeth obtained two matrices: teeth matrix and bone matrix. Until this moment, the bone matrix had not excluded dental cavities of the jaw as the segmentation process had not classified yet the teeth roots. For a three-dimensional ROI it was required the following binary operation (Equation 1):

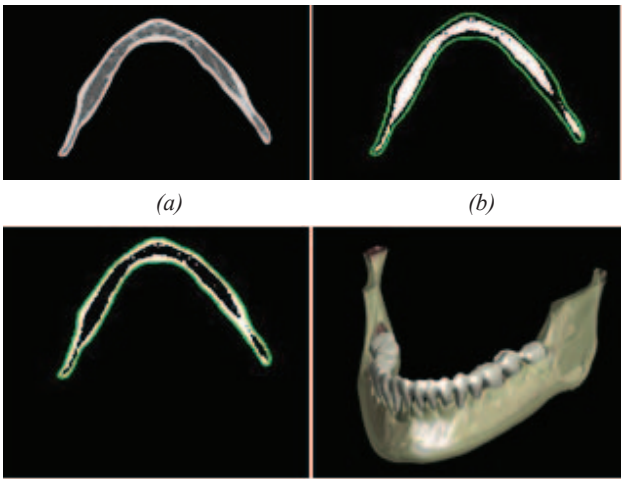
$$ROI = (M_{Bone} \oplus M_{Teeth}) \times M_{Bone} \qquad Eq.1$$

Once bone and teeth matrices were correctly extracted, classification of cortical and cancellous bone was performed.

Otsu binarization algorithm for bone classification was implemented [15] but with an amendment applicable to this case: whole set of images was used for calculating the threshold (instead of using only a slice). A probability of each gray intensity level was obtained for each one of the images, after applying the ROI mask (*Figure 2*). Probability

of 0 (this area is not bone) was removed for threshold estimation, as it could interfere with Otsu's method.

2.2. Finite Element analysis for mechanical assessment of mandibles

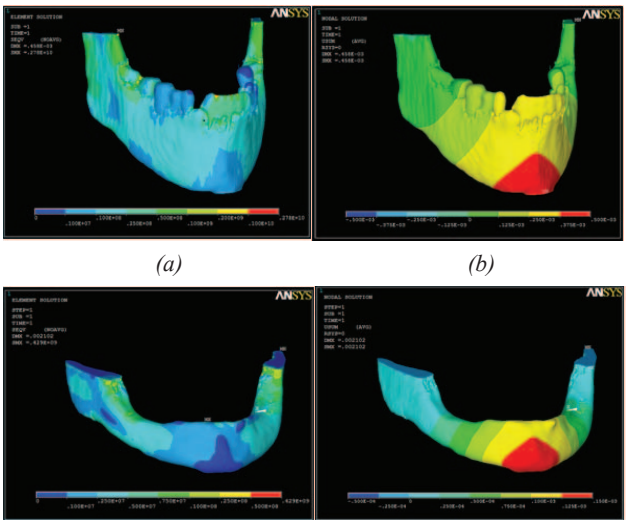


(a) *(b)* *(c)* *(d)*

***Figure 2. Bone classification**, Initial mask in slice for extracting ROIs (a) and subsequent resulting mask of cancellous (b) and cortical (c) bone; finally, 3d reconstruction with the three solid tissues differentiated (d).*

A FE linear model was used for assessing mechanical performance of mandible. To create the FEA models, the resulting matrices of segmentation were exported to ScanIP and Scan FE software, were median and morphological filters were applied to refine some of the reconstructions obtained (especially those affected by metal artifacts). Also materials properties were assigned using this software and, for the present study, they were assigned as homogenous for each solid tissue based on Pahr et al [17]. They found a high correlation between simulation and experimental studies in stiffness assessment of vertebrae bone, either with homogenized FE models or gray-based models. Material properties were defined as follows: Density (ρ), Young modulus (E) and Poisson (ν) coefficient values were found in the literature, from experiments conducted in the jawbone [18] (cortical bone: ρ=1794 kg/m^3, E=13.7 GPa, ν=0,3; cancellous bone: ρ=700 kg/m^3 , E=7.93 GPa, ν=0.3; teeth: ρ=2000 kg/m^3, E=18.6 GPa, ν=0.31).

After this, it was exported the resulting mesh into ANSYS and then simulated a load experiment, based on a model of a study that validated a simulation with experimental data in macaque jawbone [19]. Boundary conditions were defined as three translational degrees of freedom, with null displacement for the nodes corresponding to the top of the ramus. Neither of the images included the condyles, because all CT were explored below this level. Then, we applied a 130 N perpendicular load distributed along the central and lateral incisors. In edentulous jawbones the load was applied in the region that would correspond to this teeth location.



(a) *(b)* *(c)* *(d)*

***Figure 3. FEA Map Result,** (a) Von Misses stress young women's mandible. (b) Displacement sum vector young women's mandible. (c) Von Misses stress old women's mandible. (d) Displacement sum vector old women's mandible.*

3. RESULTS AND DISCUSSION

Simulations took place obtaining the following results (Mean ± SD): Von Misses stress: 6.01E+08 ± 6.379E+08 Pa; Von misses strain: 1.69E-01 ± 2.78E-01 and displacement vector sum: 1.85E-02 ± 5.25E-02 m. *Figure 3* shows Von Misses stress and displacement vector sum maps in mandibles at different stages of life.

Displacement vector sum results showed statistically significant differences (ANOVA test F=2.75, p=0.04) among different age groups, increasing as age advanced.

These results show differences in the mechanical properties of jawbone among age groups and correlate well with the founding in a previous study that used a computed based finite element analysis and showing variations in stress and strain values of mandibles at different stages of life [20]. Although this study used a different approach and measures, similar conclusions regarding age-dependent differences can be inferred from both. The effect of age with bone mineralization and with the bone mechanical properties have been discussed previously [21]. Nevertheless methods implemented for assessment of jawbone are mostly experimental and just recently, some studies have proposed numerical methods for this purpose [2].

4. CONCLUSION

This work describes the development and implementation of an algorithm that permits to classify the different tissues of the jawbone (teeth, cortical bone and trabecular bone). The created geometrical models are used for mechanical analysis by FEA. This algorithm has been applied to twenty-five CT sets of images from women at different stages of life.

Although several methods for segmentation and classification of bones are found in the literature [12,20] most are threshold-based. None of the studies have implemented active contours, which seems to fit better to the problem of extraction of jawbone tissues. Moreover, we think that a semi-automatic method could allow manually corrections of possible errors in the extraction process and would make results more accurate.

Innovative solutions have been implemented in the extraction process. For example, classification of image pixels that are part of the teeth was not trivial because there are no clearly defined contours in some areas, as in the roots, so it was necessary to seek a different approach. Modeling was the optimal solution for segmentation of the roots of teeth and the method showed a good performance yet it requires to be improved.

One important limitation is that CT scan images could be corrupted by the presence of streaking artifacts from metal materials -as implants and amalgam fillings- and could interfere in the performance of the segmentation method and the resulting geometrical model. Many different approaches for metal artifact reduction (MAR) are found in literature [22], most of which implemented in acquisition and reconstruction steps of CT imaging, with only a few and insufficient solutions for highly corrupted images. Nevertheless, some corrupted images were analyzed because artifacts effects could be slightly reduced by preprocessing steps.

The preliminary results obtained could differentiate biomechanical jaw parameters among life span in women.

5. ACKNOWLEDGEMENTS

The support of the Spanish Ministry of Science and Innovation through project TEC2009-14128 is acknowledged.

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