containing two different experiments. In the first experiment we measure how realistic predictions are without knowing the real post-operative facial outlook. In the second experiment we score the qualitative correspondence of our prediction with respect to the real post-operative facial appearance.

An overall median score of 4 on a 1 to 5 scale was achieved when measuring the accuracy of the predicted facial appearance in comparison with the real post-operative facial outlook. Moreover 80% of the surgeons agreed that they would use the presented soft tissue predictor in daily clinical practice to improve the bone-related planning and to ameliorate communication between surgeon and patient. Secondly we conclude after comparison of results of the qualitative and quantitative validation, that the nose and lip region need special attention in our soft tissue predictor. Defining proper boundary conditions for those regions will be our primary future goals. At last we can conclude from this study that it is important that the patient's face is in a natural and relaxed position during pre-operative CT acquisition.

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References

1. Schutyser F, Van Cleynenbreugel J, Ferrant M, Schoenaers J, Suetens P (2000) Image-based 3D planning of maxillofacial distraction procedures including soft tissue implications. Lecture notes in computer science (MICCAI) 1935, 999–1007
2. Chabanas M, Marecaux C, Chouly F, Boutault F, Payan Y (2004) Evaluating soft tissue simulation in maxillofacial surgery using preoperative and postoperative CT scans. In: Proceedings of CARS, pp 419–424
3. Mollemans W, Schutyser F, Nadjmi N, Maes F, Suetens P (2006) 3D soft tissue predictions with a tetrahedral mass tensor model for a maxillofacial planning system: a quantitative validation study. In: Proceedings of SPIE
4. Maes F, Collignon A, Vandermeulen D, Marchal G, Suetens P (1997) Multimodality image registration by maximization of mutual information. IEEE Trans Med Imaging 16(2):187–198
5. Mollemans W, Schutyser F, Nadjmi N, Suetens P (2005) Very fast soft tissue predictions with mass tensor model for maxillofacial surgery planning systems. In: Proceedings of CARS, pp 491–496
6. Sarver D (1997) Esthetic orthodontics and orthognathic surgery, 1st edn. Mosby, St. Louis

A 3D computer-assisted method for the strategy and assessment of therapy of the weakened mandible

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Abstract Mandible can be weakened by cysts, tumors or natural bone resorption The goal of our research is both to set-up and to assess a computerized tool to analyze the 3D CT-Scan images of the patient and explore mandibular biomechanics in order to assist the practitioner in the treatment of the weakened mandible. First results have been obtained and are presented in the paper.

Keywords Mandible · Edentulous · Fracture · 3D Image processing · Biomechanics · FEM simulation

1 Introduction

Departments of Maxillofacial Surgery and Stomatology receive every year patients with mandible that are lysed, resected or edentulous because of age or tumoral disease.

The loss of substance due to cysts or tumors weakens the ramus and corpus of the mandible. This weakness leads to fracture risk during chewing, especially when the maxillofacial surgeon cuts part of the mandibular bone in an interrupting way or not.

Moreover, the loss of teeth induces the resorption of the bone surrounding the roots, named alveolar bone. Indeed, this bone is known to ''rise and die with teeth''. This resorption is ineluctable, chronic and may be different from a patient to another (age, sex, hormonal state,...). The bone height and thickness diminution also leads to a mandibular weakness that increases fracture risk and makes repair harder. The bone loss can be up to 65% of the initial volume [1].

The goal of our research is both to set-up and to assess a suite of computerized tools that will analyze the 3D CT-Scan images of the patient and assist the maxillofacial practitioner in clinical routine.

This requires to design patient-specific geometrical and biomechanical models of the mandible and to apply masticatory forces, which are specific to the patient to be treated (with respect to age, alimentary habits and anatomy). Then, bone strains and stresses are computed and analyzed by using finite elements method (FEM).

Medical applications are the prediction of the fracture risk threshold that will dictate the treatment decision; planning and simulating a therapy (for example by defining the critical height of the mandible to be preserved in case of a tumoral surgery) and assessing the therapy by a retrospective evaluation of the clinical case and a correlation with the computed results.

Many studies have used FEM models to evaluate the mechanical strains and stresses developed within the mandibular bone (e.g. [2–4]) but most of them deal with the behavior of the bone material located near dental implants [5, 6]. Thus, the biomechanics of the edentulous mandible remains not well known so far [7].

2 Methods

The project gathers a multidisciplinary team comprised of medical doctors (maxillofacial surgeons, radiologists), biomechanics specialists and computer scientists from different institutions. The method workflow is shown in Fig. 1.

1. CT-Scan acquisition of the patient's jaw. A precise acquisition protocol (resolution, position, field of view) is defined in order to acquire accurate information on both the mandible and the surrounding muscles.
2. 3D-Visualization/interaction. In order to check the images and localize anatomical landmarks, we use the medical image review and aided diagnosis software Myrian® developed by the company Intrasense (http://www.intrasense.fr).
3. 3D Segmentation of the mandible. We delineate the contours of the mandible bony structure by using the semi-automatic 3D segmentation tools provided in Myrian® software. For instance, we pay a particular attention to the segmentation of both the tooth roots and the temporo-mandibular joint.
4. Automatic extraction of the mandible 3D surface mesh.
5. Adapted volumetric meshing of the mandible interior in order to apply the FEM software Dynel® developed by the company IGEOSS (http://www.igeoss.com).
6. Mesh alteration to simulate surgical bone cut or ''natural'' bone resorption [8].
7. Muscle insertion localizations in the 3D image, definition of the physical parameters (e.g. material properties, Young modulus and Poisson's ratio, elastic limits or fatigue, etc.) and of the applied boundary conditions (e.g. chewing scenario and pressure parameters) [9].
8. FEM computation and 3D visualization of the results. For this purpose, we also use the FEM software Dynel®.

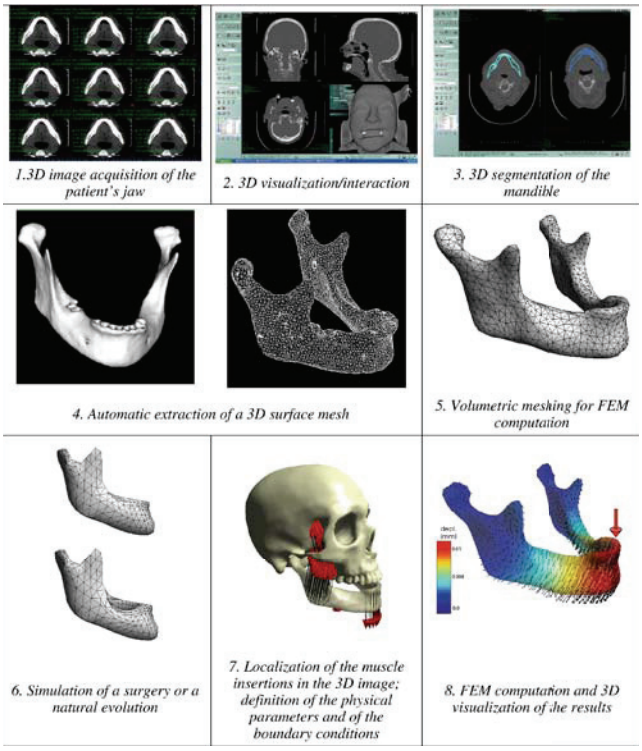

Fig. 1 Method workflow

3 Results

A high resolution (voxel size: $0.449 \times 0.449 \times 0.65$ mm^3) 3D image of an edentulous patient was acquired with a General Electric Light Speed 16 CT-Scan device.

We defined the following biomechanical scenarios:

- Application of a 10 kg chewing force on a molar region (scenario 1) or a 5 kg biting forces on the anterior dental region (scenario 2),
- Application of the muscular forces necessary to preserve the mandibular balance.

Resulting deformations are shown in Figs. 2 and 3 by visualizing the 3D displacement field and the intensity of the Von Mises stress criterion.

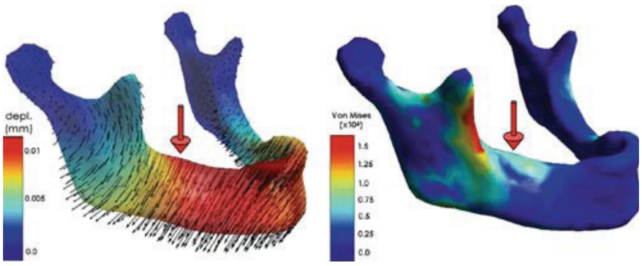

Fig. 2 3D Visualization of the displacement field (*left*) and of the Von Mises criterion (*right*) for scenario 1

The results of this preliminary study show that chewing on a weakened mandibular zone (molar region) causes important stresses of the basilar rim of the cortical bone. Another predictable observation is that important stresses can be observed on the muscular insertions and on the force application point (see the red arrow in Fig. 2). Smaller stresses can be observed while biting on a non weakened mandible (see Fig. 3).

4 Discussion

In the left hand side of Figs. 2 and 3, we notice the rotation axis of the system, in the condylar region, where the displacement vectors are smaller. In scenario 1, the maximum displacement of the corpus is

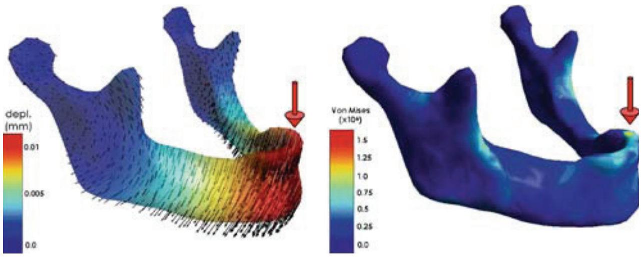

Fig. 3 3D Visualization of the displacement field (*left*) and of the Von Mises criterion (*right*) for scenario 2

higher on the right side of the mandible than on the left side because the chewing force is applied on the right part of the mandible.

We can also observe important stresses in the chewing application zone (right corpus). Moreover, increasing stresses are seen around the muscular insertions (right angle, right ramus anterior rim). We conclude that the FEM model appears appropriate for stress analysis caused by chewing forces.

Nevertheless, the 5 and 10 kg forces we chose to apply on the mandible are generic and cannot exactly fit every patient. In the future, we plan to estimate the mastication force by measuring the cross-sectional area of the elevator muscles in the 3D image.

Moreover, we have to assess the system by comparing the FEM modeling of a virtually resected mandible with the FEM modeling of the same mandible after being surgically weakened.

5 Conclusion

We are currently improving the different steps of the method. In particular, we plan to develop fully automatic 3D segmentation algorithms in order to precisely and quickly delineate the teeth and detect the temporo-mandibular joint. We will also analyze the relationship between the biomechanical properties of the mandible and the CT-Scan image intensity in order to automatically attribute physical parameters to the 3D FEM model.

Our long-term goal is to study different image processing methods to reduce image artefacts caused by dental amalgam. An other challenging topic would be to segment the muscles in order to detect their insertion areas for a better constrained FEM model.

More generally, in the future, such computerized tools could be connected to a robotic system to assist the guidance of a milling device for drilling or cutting-up bone tissues in maxillofacial surgery as it is found in orthopedics.

References

1. Vacher C (2004) Anatomie du vieillissement cranio-facial. Encycl Med Chir Stomatologie 22-052-A-05: 9
2. Weingärtner T, Hassfled S, Dillmann R (1997) Dynamic simulation of the jaw and chewing muscles for maxillofacialsurgery. Nonrigid and articulated motion workshop. In: Proceedings of IEEE, pp 104–111
3. Vollmer D, Meyer U, Joos U, Vegh A, Piffko J (2000) Experimental and finite element study of human mandible. J Craniomaxillofac Surg 28(2):91–96
4. Erkmen E (2005) Three-dimensional finite element analysis used to compare methods of fixation after sagittal split ramus osteotomy: setback surgery-posterior loading. Br J Oral Maxillofac Surg 43(2):97–104
5. Fütterling S, Klein R, Straßer W, Weber H (1998) Automated finite element modelling of a human mandible with dental implants. In: Sixth international conference in Central Europe on computer graphics and visualization, Plzen – Bory, Czech Republic
6. Nagasao T, Kobayashi M, Tsuchiya Y, Kaneko T, Nakajima T (2002) Finite element analysis of the stresses around endosseous implants in variaous reconstructed mandibular models. J Cranio Maxillofac Surg 30:170–177

7. Veyrune JL (2000) Evaluation de la fonction masticatoire chez les sujets totalement édentés appareillés. Cah Prothèse 110:47–55
8. Pierrisnard L (1994) Comportement mécanique des structures dentaires et osseuses. Analyse par la méthode des éléments finis. Cah Prothèse 88:7–13
9. Kober C (2004) Adaptative finite element simulation of the human mandible using a new physiological model of the masticatory muscles. Proc Appl Math Mech 4:332–333