ANISOTROPIC COMPUTATIONAL DESCRIPTION OF BONY ELEMENTS: A JAW STUDY

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CT data

Aim

Nowadays, the need of **computational clinical tools** for intervention planning and effectiveness evaluation is increasing in demand. High accuracy, patient specificity and real-time results are crucial factors. The **aim** of the research activities consists in the implementation of an almost **automatic procedure** for the characterisation of bone tissue mechanical behaviour starting from *in vivo* CT data. The procedure is customized for the patient and the bony element.

Materials and Methods

Steps of the implemented procedure:

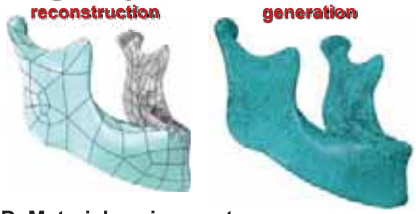
A. CT segmentation and virtual solid model.

B. Definition of FE model.

The virtual solid model is imported into the FE pre-processor Abaqus CAE 2018 (Dassault Systèmes Simulia Corp., Providence, RI). A standard mesh composed by unstructured four-node tetrahedral elements is defined. Different mesh seeds are assumed.

C. Material property extraction.

- **constitutive tensors** are based on a micromechanics formulation [1]. The non-zero components of the pure cortical bone tensor are customized for the jaw [2].
- **principal material directions** are defined as the eigenvectors of the **HU "inertia" matrix**.



HU "inertia" matrix

$$\mathbf{M} = \begin{bmatrix} \sum_i HU_i\,(y_i^2+z_i^2) & -\sum_i HU_i\,x_i y_i & -\sum_i HU_i\,x_i z_i \\ -\sum_i HU_i\,y_i x_i & \sum_i HU_i\,(x_i^2+z_i^2) & -\sum_i HU_i\,y_i z_i \\ -\sum_i HU_i\,z_i x_i & -\sum_i HU_i\,z_i y_i & \sum_i HU_i\,(x_i^2+y_i^2) \end{bmatrix}$$

D. Material assignment.

Different mapping strategies are implemented, which consider:

- the material properties of the nearest voxel (**NVS**, Nearest Voxel Strategy);
- the averaged material properties of the three nearest voxels (**TNVS**, Three Nearest Voxels Strategy).

E. Discrepancy quantification.

Error Rate $= \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{c^{ME,i}-c^{V,i}}{c^{V,i}}\right)^2}$, N is the number of CT voxels, $c^{(ME,i)}$ is a property of the i-th element of the mesh, while $c^{(V,i)}$ is the property of the corresponding voxel. The property c is the Young's elastic modulus along the major stiffness direction.

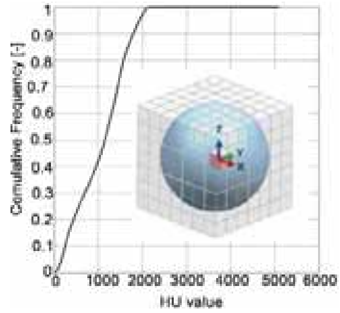


***Fig.1**: Plot of the cumulative frequency analysis and spherical voxel set used for the detection of the principal material directions.*

Results

- The procedure respects the differentiation between trabecular and cortical bone, detectable from CT scan (Fig. 2).
- The NVS strategy provides the better results but the mesh element dimension affect the results (Fig. 3).

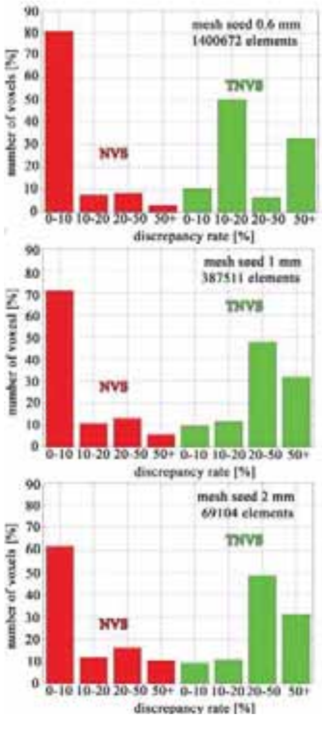


***Fig.3**: Histograms of the estimated discrepancy rate for different mean element sizes.*

- The detection of the maximum principal material direction is proposed in Fig. 5.
- Validation of the biomechanical model by conserving a structural test [4] (Fig.4).

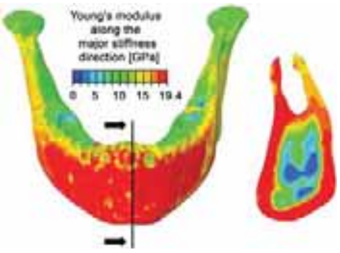


***Fig.2**: Color maps of the material properties distribution.*

biomechanical structural test

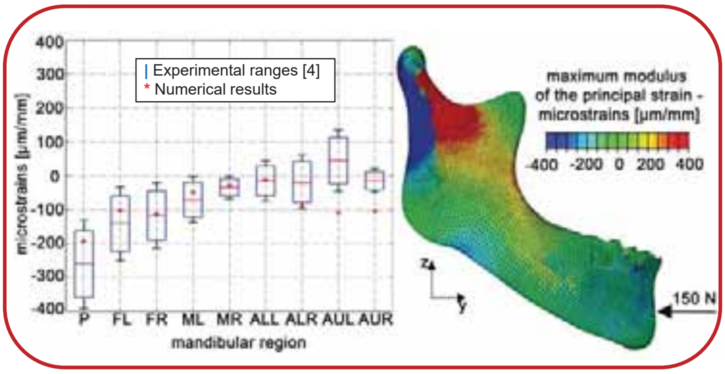


***Fig.4**: Comparison between experimental ranges [4] and numeric results in terms of microstrains. P – Pogonion, FL - mental Foramen Left, FR - mental Foramen Right, ML - Molar region Left, MR - Molar region Right, ALL - mandibular Angle Lower Left, ALR - mandibular Angle Lower Right, AUL - mandibular Angle Upper Left; AUR - mandibular Angle Upper Right (a).*

detection of the directions of anisotropy

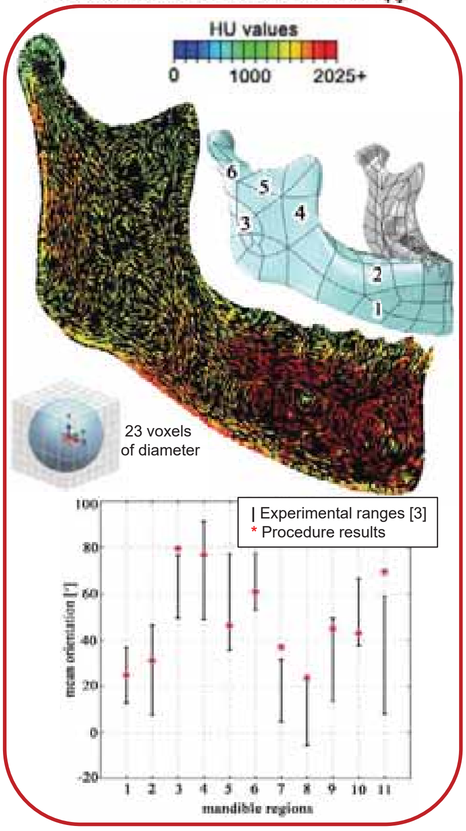


***Fig.5**: Detection of the direction of anisotropy along the major stiffness direction.*

Discussion

The achieved results point out the capability of the procedure in supplying **subject specific** models of **bony structures** starting from *in vivo* CT data. The good matches with experimental results highlight the procedure's great potentialities and its accuracy and almost automatism give the basis to develop a clinical tool. There are still open questions principally regard the size of the neighbourhood for the identification of material principal directions.

References

1. Hellmich et al., "Micromechanics-Based Conversion of CT Data into Anisotropic Elasticity Tensors, Applied to FE Simulations of a Mandible", 2008.
2. Ashman and Van Buskirk, "The Elastic Properties of a Human Mandible",1987.
3. Dechow et al., Primate Craniofacial Function and Biology. Developments in Primatology: Progress and Prospects. Boston (MA): Springer, 2008, ch 13.
4. Meyer et al., "Experimentelle und Finite-Elemente-Analyse der Biomechanik des Unterkiefers unter Belastung", 2000.

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