A continuum damage mechanics based bone remodeling model in a finite strains framework.

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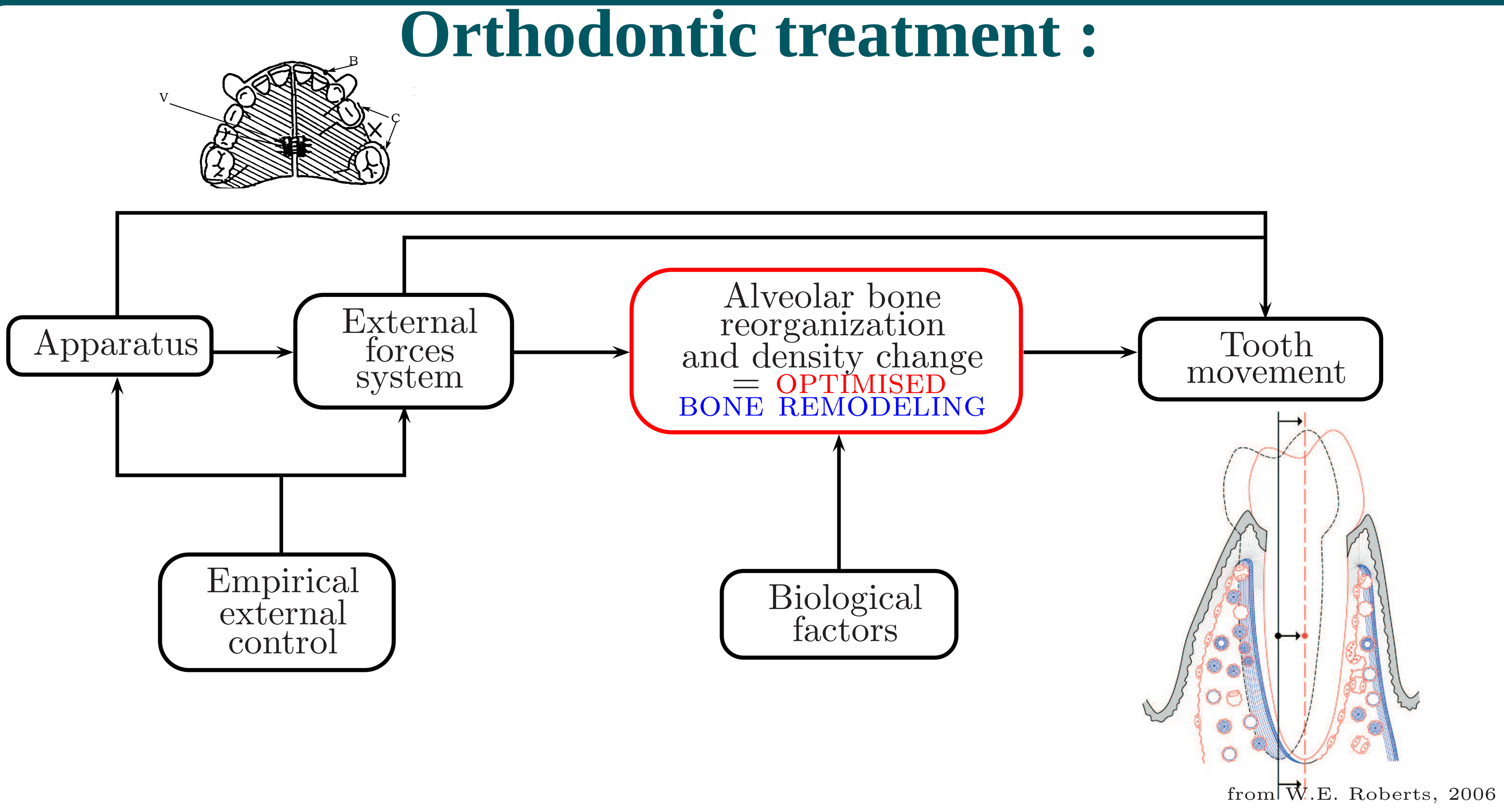
Orthodontic treatment :



Bone remodeling = optimized bone mechanical response.

BUT orthodontic treatment plans mainly based on empirical knowledge ≠ optimized treatment (mathematically speaking).

Aim : get a contribution to a treatment model

⇒ **model** bone remodeling on a **macroscopic** scale (**phenomenological** model)

Hypothesis : trabeculae mechanical behavior : **elasto-plasticity**

bone fibers alignment : orientation given by **fabric tensor**

bone density adaptation : $\dot{\rho} = kS_v\dot{r}\rho_0$

Mechanical **framework** : **finite strains**

continuum damage *formulation*

(**no** actual damage of the trabeculae) [1, 2]

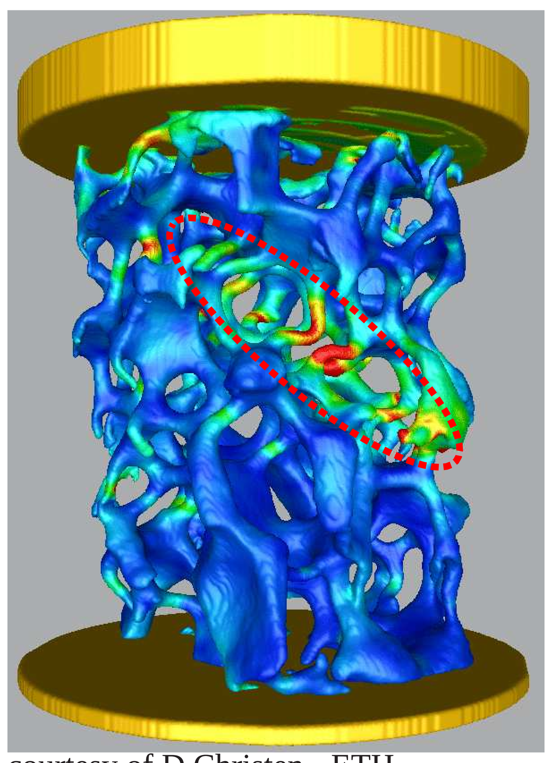
finite element simulation (using Metafor [3])

Testing the hypothesis :

Aluminium foam compression tests - non linear simulation / exp. data

Work done in collaboration with ETH - Institute of Biomechanics
Simulation results acquired after abstract submission.

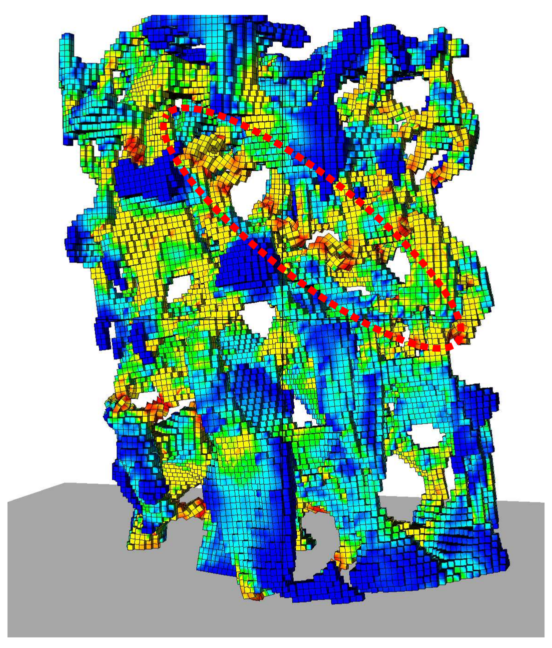
Exp. Data



courtesy of D.Christen - ETH

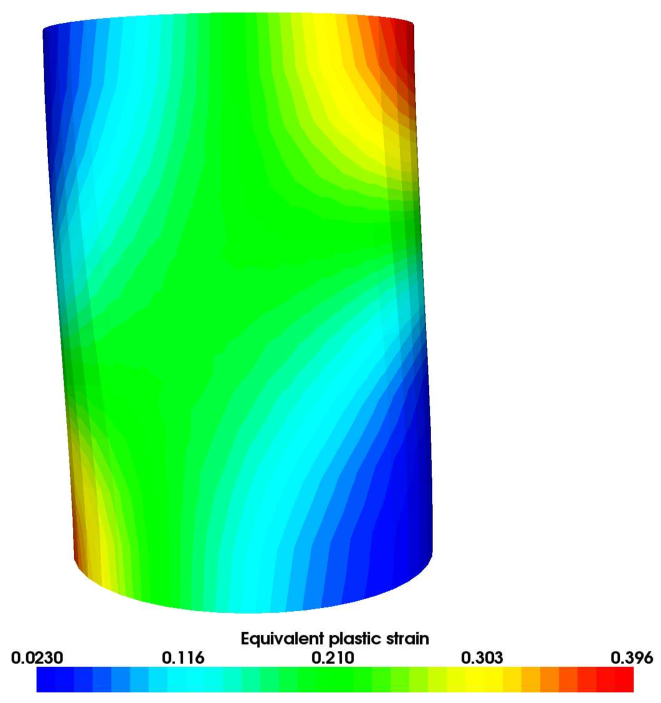
μ-FEM

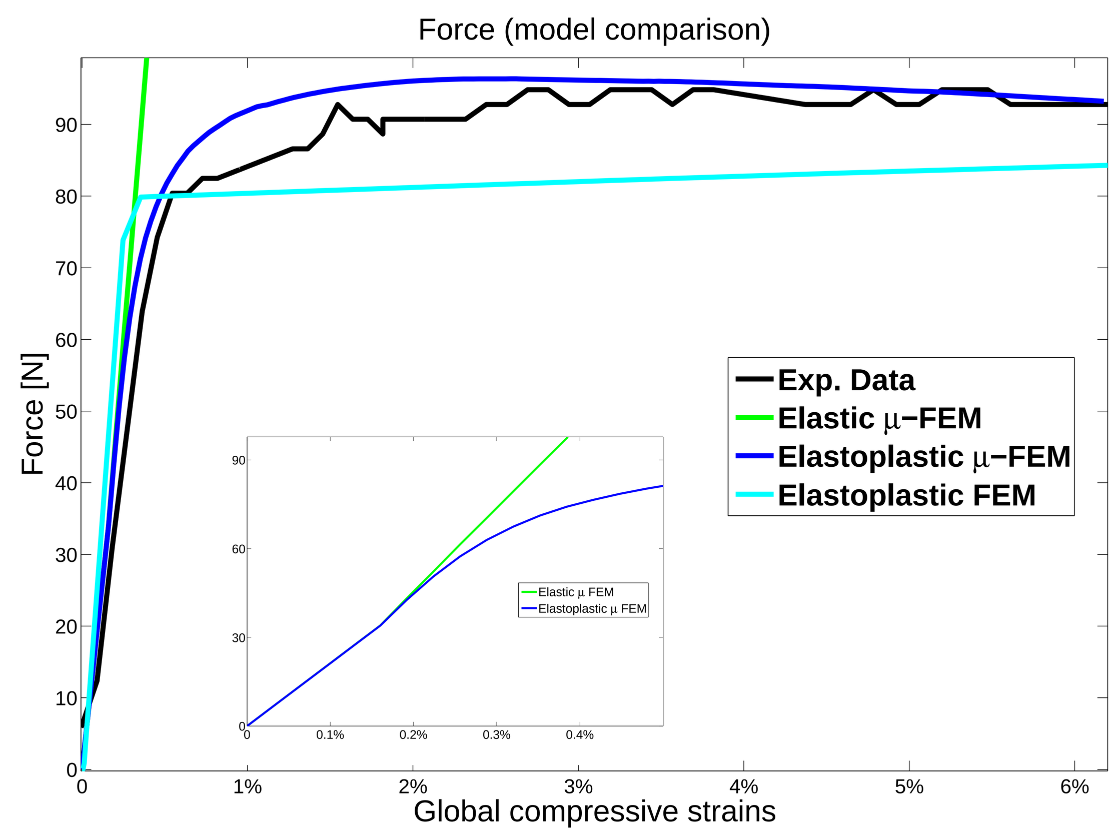
geometry from CT-scans



FEM

fabric and apparent density derived from morphology data





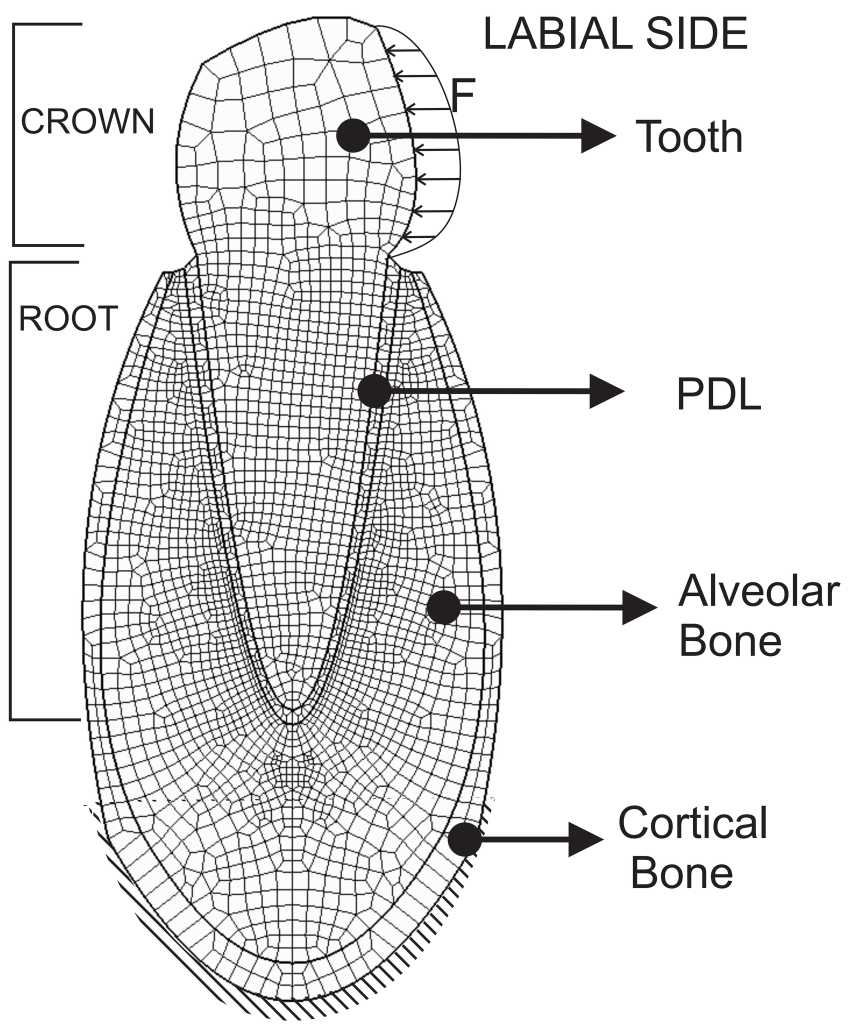
Both the **overall deformation pattern** and **localization of high strains areas** are well accounted for in the μ-FEM simulation. Highest strains appear to be on a plane where the apparent density is low. **Significant differences between elastic and elasto-plastic simulations appear from** 0.4% **global compressive strains.**

The use of a **fabric tensor**, **homogeneous** on the all Al. foam cylinder, allows to **represent** the **overall sample deformation** and the **external force**. It is **not enough** to represent **failure** plane. Fabric tensor models can therefore be used only on smaller **representative volumes**.

Preliminary results on remodeling :

Orthodontic treatment simulation : 2D idealized tooth

buccolingual plane

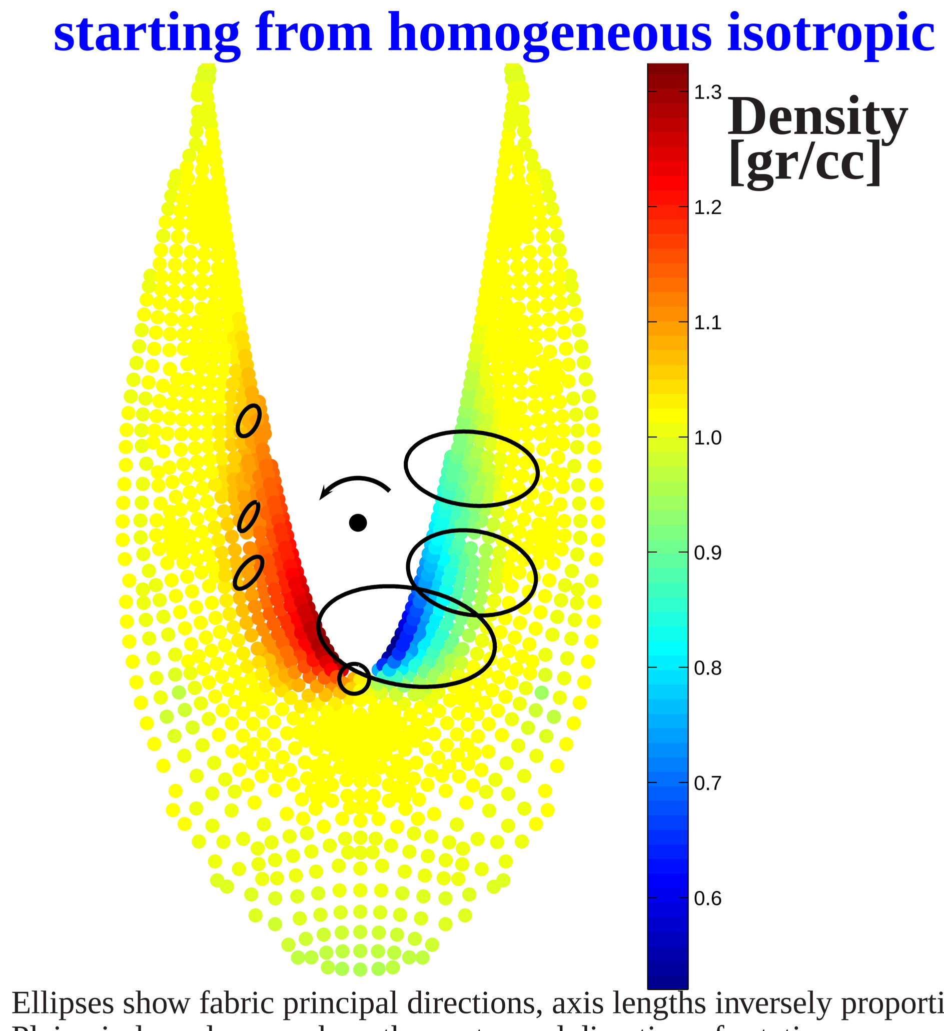


- Idealized 2D geometry : parabolic root
  plane strain state
- Linear elastic tooth and PDL
- Fabric-related elasto-plastic alveolar and cortical bone
- No gengiva
- Boundary conditions : constrained basal bone
  labial pressure force on the crown
  ≡ **orthodontic loading, tipping**
  (buccolingual rotation)

Results :

- Resorption and formation occur to allow tooth migration (**simulation can represent in-vivo behavior**)
- Trabecular orientation aligns so that bone fibers are perpendicular to the tooth root surface, except at the apex where the pressure switches from tension to compression

remodeling after 3 weeks of constant loading starting from homogeneous isotropic bone



Ellipses show fabric principal directions, axis lengths inversely proportional to density
Plain circle and arrow show the center and direction of rotation

Ongoing/Future work :

Non linear behavior : validation

Validation of the FE analysis for 5 different samples, 3 densities (15 samples total).

Mesh convergence : use of at least 3 mesh resolutions

BC's representation : comparison of constrained/contact BC's

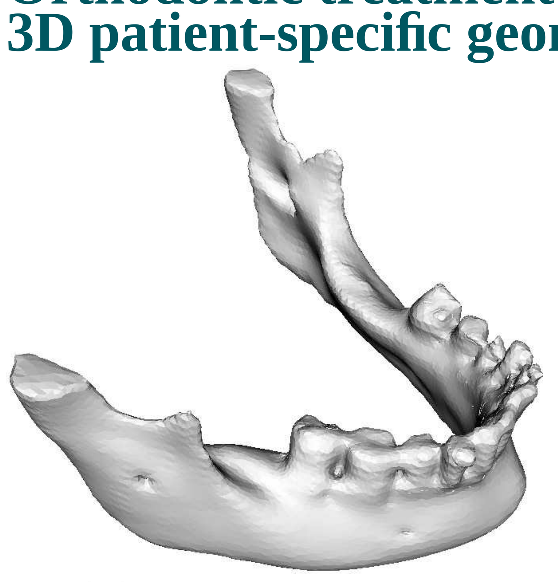
Type of integration : comparison of explicit, implicit and quasi-static FE analysis

Fabric/CDM formulation

Defining representative volumes for fabric.

Computing SED difference between continuum and μ−FEM (aim : no difference).

Orthodontic treatment simulation : 3D patient-specific geometry



courtesy of V. d'Otreppe - ULg

Construction of patient-specific geometry (mesh from home-made triangulation mesher from CT-data)

Forces system from CAD-designed orthodontic appliances

Acknowledgment to

D. Christen, D. Ruffoni, R. Voide and G.H. van Lenthe, ETH Zurich

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

References

[1] M. Doblaré and J.M. García. Anisotropic bone remodelling model based on a continuum damage-repair theory. *J. Biomech.*, 35(1):1–17, Jan 2002.

[2] M. Mengoni and J.P. Ponthot. Isotropic continuum damage/repair model for alveolar bone remodeling. *J. Comp. Appl. Math.*, 234(7):2036–2045, Jun 2010.

[3] METAFOR, A large strain finite element code, LTAS - MN2L / University of Liège, http://metafor.ltas.ulg.ac.be/ (2010).