A Cast3M function to solve bone growth and remodeling problems

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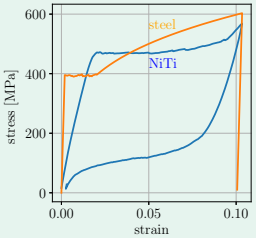
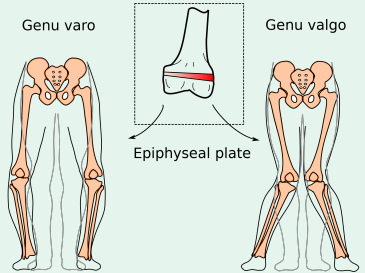
Context and motivation

SMA's mechanical behavior



Research interest

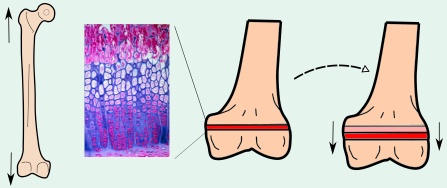


We know mechanical loads can alter growth.

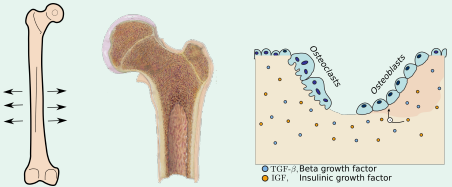
We need to define the magnitude of the load.

Problem description

Longitudinal growth



Bone remodeling

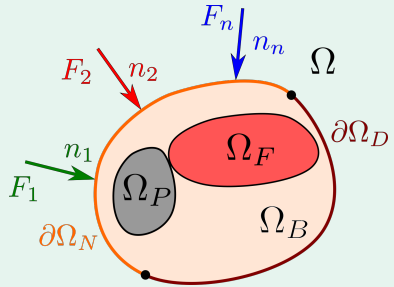


Highlights

- Longitudinal growth stops at late adolescence.
- Both mechanisms depend on multiple (stochastic) factors.
- Mechanical loads interact with growth and remodeling.
- Distinctive speeds:
  - Longitudinal growth: $\sim \frac{\mathbf{mm}}{\mathbf{month}}$
  - Remodeling: $\sim \frac{\boldsymbol{\mu m}}{\mathbf{month}}$.

Problem posing

Mathematical domain



'State' functions

- $M(\vec{r}, t)$
- $\rho(\vec{r}, t)$

Phenomenological equations

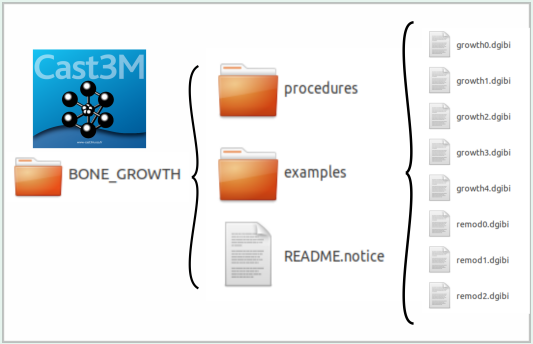
- $\mathbf{E}(\rho, M, \vec{r}, t)$
- $\dot{M}(M, \sigma_1, ..., \sigma_n, n_1, ..., n_n, \mathbf{E}, t)$
- $\dot{\varepsilon}(M, \sigma_1, ..., \sigma_n, n_1, ..., n_n, \mathbf{E}, t)$
- $\dot{r}(M, \sigma_1, ..., \sigma_n, n_1, ..., n_n, \mathbf{E}, \rho, t)$
- $S_v(\rho) \quad (\dot{r} \rightarrow \dot{\rho})$

Initial conditions

- $\rho_0(\vec{r}), M_0(\vec{r}), \sigma_0(\vec{r})$

Software

Cast3M function



* M.G. Alonso, A. Yawny and G. Bertolino, A tool for solving bone growth related problems using finite elements adaptive meshes. Journal of the Mechanical Behavior of Biomedical Materials (2021), doi: https://doi.org/10.1016/j.jmbbm.2021.104946. (In press)

Highly customizable, verified code. Several implementation examples.

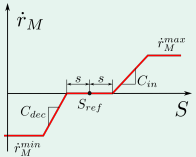
Significant improvements of growth algorithm.

Devices optimization, from an engineering standpoint.

Default implemented model

Remodeling equations

$\dot{r}(\vec{r},t) = \dot{r}_B(\vec{r},t) + \dot{r}_M(\vec{r},t)$



$S = \sum_i (n_i \overline{\sigma}_i^m)^{1/m}$
$\dot{\rho} = S_v(\rho)\rho_c \dot{r}$
$S_v(\rho) = (\frac{\rho}{\rho_c})^2 \mathscr{P}^6(\rho)$

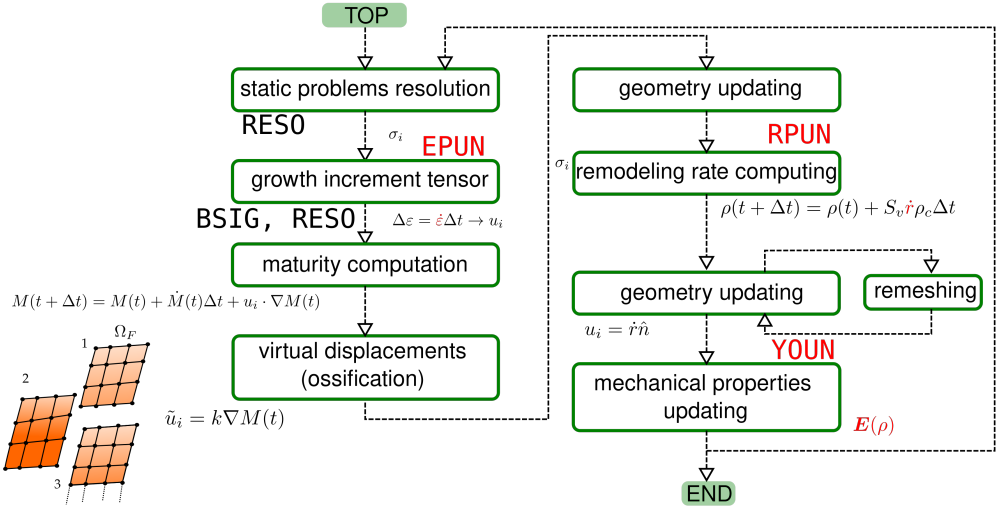
Based on Beaupré G.S., Orr T.E., Carter D.R. An approach for time-dependent bone modeling and remodeling. application: A preliminary remodeling simulation J. Orthop. Res., 8 (1990), pp. 662-670

Growth equations

$\dot{\varepsilon}_{ij} = (\dot{\varepsilon}_M + \dot{\varepsilon}_B)\varepsilon_{ij}$
$\dot{\varepsilon}_M = \kappa_M \sum_{i=1}^{k} n_i \sigma_{hi}$
$\dot{M}(\vec{r},t) = \sum_i \dot{\varepsilon}_{ii}(\vec{r},t)$

Based on Giorgi M., Carriero A., Shefelbine S., Nowlan N. Effects of normal and abnormal loading conditions on morphogenesis of the prenatal hip joint: application to hip dysplasia J. Biomech., 48 (2015), pp. 3390-3397

Algorithm


TOP
static problems resolution
RESO
σ_i
EPUN
growth increment tensor
BSIG, RESO
$\Delta\varepsilon = \dot{\varepsilon}\Delta t \rightarrow u_i$
maturity computation
$M(t+\Delta t) = M(t) + \dot{M}(t)\Delta t + u_i \cdot \nabla M(t)$
Ω_F
1
2
3
virtual displacements (ossification)
$\tilde{u}_i = k\nabla M(t)$
geometry updating
RPUN
σ_i
remodeling rate computing
$\rho(t+\Delta t) = \rho(t) + S_v\dot{r}\rho_c\Delta t$
geometry updating
remeshing
$u_i = \dot{r}\hat{n}$
YOUN
mechanical properties updating
$\boldsymbol{E}(\rho)$
END

Usage

Input

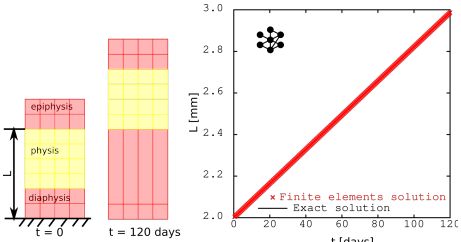
```
(TAB2 = ) BONE_GROWTH TAB1;
TAB1 = TABL;
TAB1.'BONE' (MAILLAGE)
TAB1.'LOADS' (TABLE)
TAB1.'DENSITY' (CHPOINT)
TAB1.'CALCULATED_TIMES' (LISTREEL)
(TAB1.'PHYSIS' (MAILLAGE))
(TAB1.'PROSTHESIS' (MAILLAGE))
```

Output

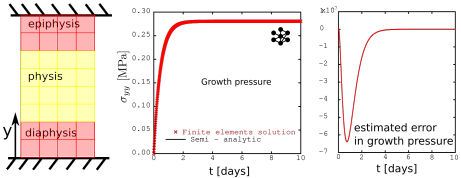
```
TAB1 = TABL;
TAB1.'RESULTS'.(I) = TABL;
TAB1.'RESULTS'.(I).'TIME' (REEL)
TAB1.'RESULTS'.(I).'MODEL' (MMODEL)
TAB1.'RESULTS'.(I).'DENSITY' (CHPOINT)
TAB1.'RESULTS'.(I).'MATERIAL' (MCHAML)
TAB1.'RESULTS'.(I).'STRESS' (MCHAML)
```

More details in file README.notice

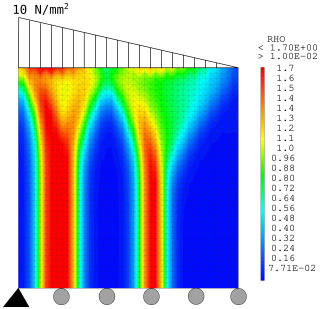
Some validation cases



growth0.dgibi: Free longitudinal growth.

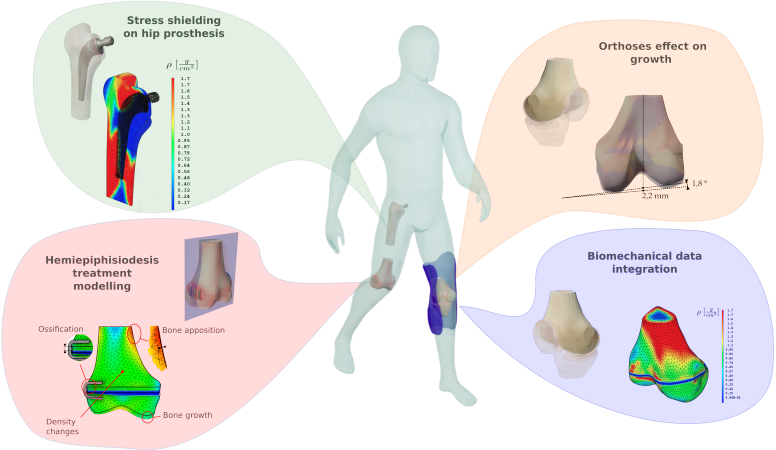


growth1.dgibi: Constrained longitudinal growth.



remod0.dgibi: Theoretical cases studied by Weinans, H., Huiskes, R., Grootenboer, H. J., "The behavior of adaptive bone remodeling simulation models", J. Biomechanics, Vol. 25. No. 12 pp 1425-1441, 1992

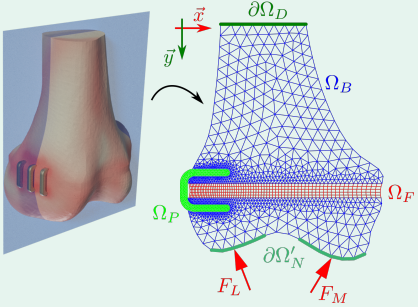
Selected cases



Cast3M + SALOME + blender

2D model of a hemiepiphysiodesis treatment

Problem posing

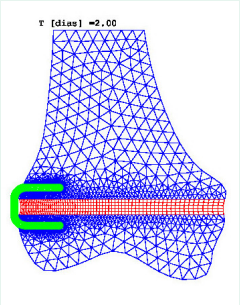


Load state	F_L [N/mm]	F_M [N/mm]	n
1	15	15	6000
2	0	7.5	3000
3	7.5	0	3000

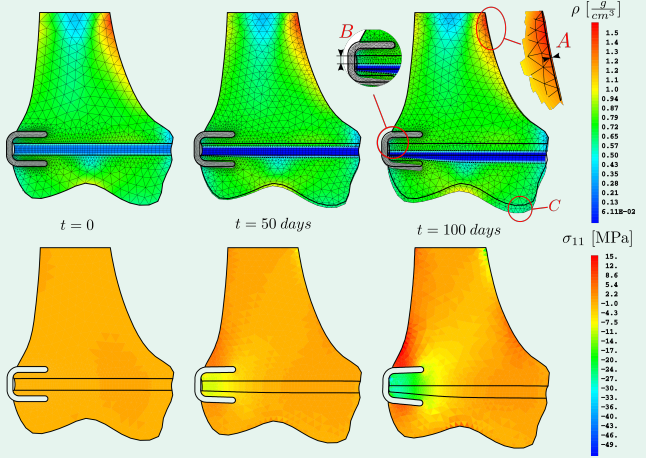
growth3.dgibi

Growth evolution

Geometry evolution

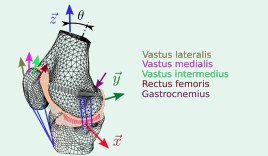


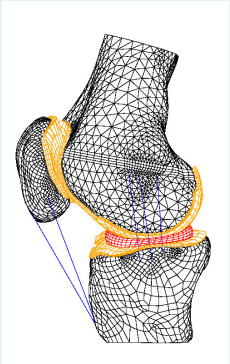
Quantities of interest



Knee model

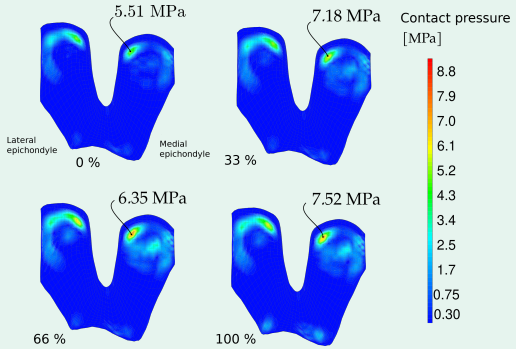
Contact problem





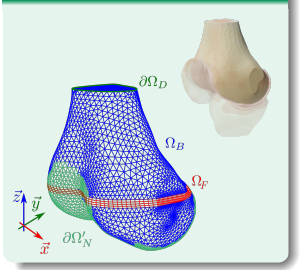
* Steele K, Seth A, Hicks JL, Schwartz MS, Delp SL. Muscle contributions to support and progression during single-limb stance in crouch gait. Journal of Biomechanics 2010;43:2099-2105.

Pressure distribution

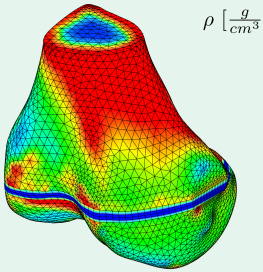


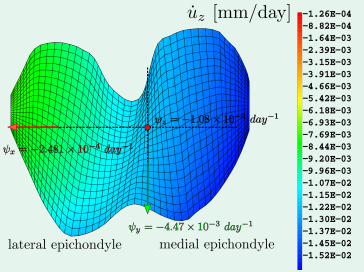
Estimated growth and bone density.

Problem posing



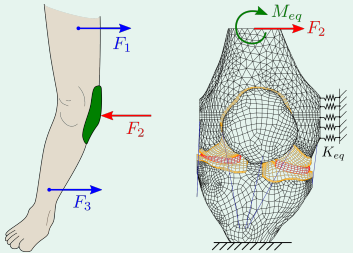
Tissue density and growth speed



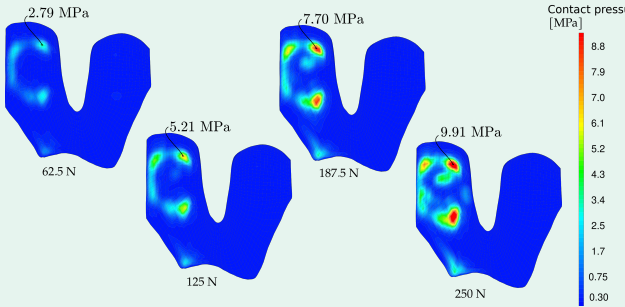


Loads determination

Contact problem

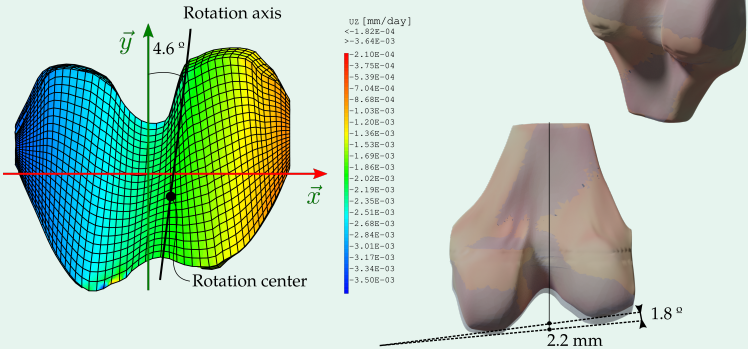


Stress on the femoral cartilage



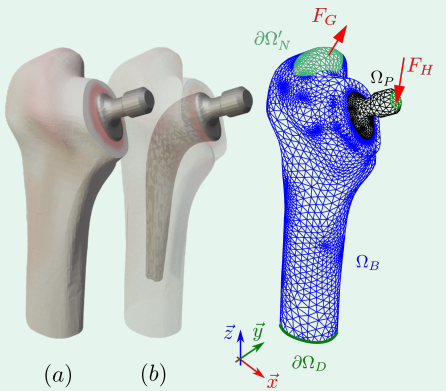
Growth after three months

Growth speed and geometry changes



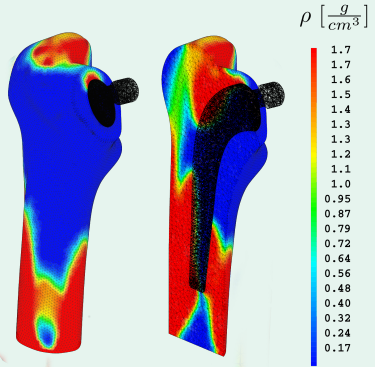
"Stress shielding" on hip prosthesis

Boundary conditions



* Garijo N, Fernandez JR, Perez MA, García-Aznar JM. Numerical stability and convergence analysis of bone remodeling model. Comput Methods Appl Mech Engrg 2014;271:253

Equilibrium density distribution



Conclusions

- An ad-hoc Cast3M function to solve bone growth and remodeling problems was created. A default phenomenological model was chosen.
- A significant computational cost reduction was achieved for growth problems (not shown here).
- Code was validated against analytically obtained solutions, or previously published data when possible.
- The sofware gives a foundation for solving practical interest problems, in which
  - an orthopedic device interacts with growing bone,
  - biomechanical data needs to be considered,
  - external orthotic devices are to be designed
  - or custom made orthotics need to be optimized.
- All the code, meshes and validation cases have been published (doi: https://doi.org/10.1016/j.jmbbm.2021.104946)

Thanks for your attention.

https://fisica.cab.cnea.gov.ar/metales/

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