Electro-mechanically driven bone remodelling using the proposed open-source framework

For the benchmarking of the proposed open-source framework for bone remodelling studies, an electro-mechanically driven bone remodelling model (Alvarado et al. 2012) was analysed. A classical 2D plate model (see Fig 1) representing the cross-section of bone tissue was simulated and the results obtained are compared with those reported in the study by Alvarado et al. 2012. The square plate of size 0.1 x 0.1 m was meshed with quadrilateral elements in FEniCS. For the electro-mechanically driven model, the mechanical boundary conditions shown in Fig 1a were coupled with electrical boundary conditions (Fig 1b). For this model, plane stress condition is assumed and the simulation is performed under the small displacement theory.

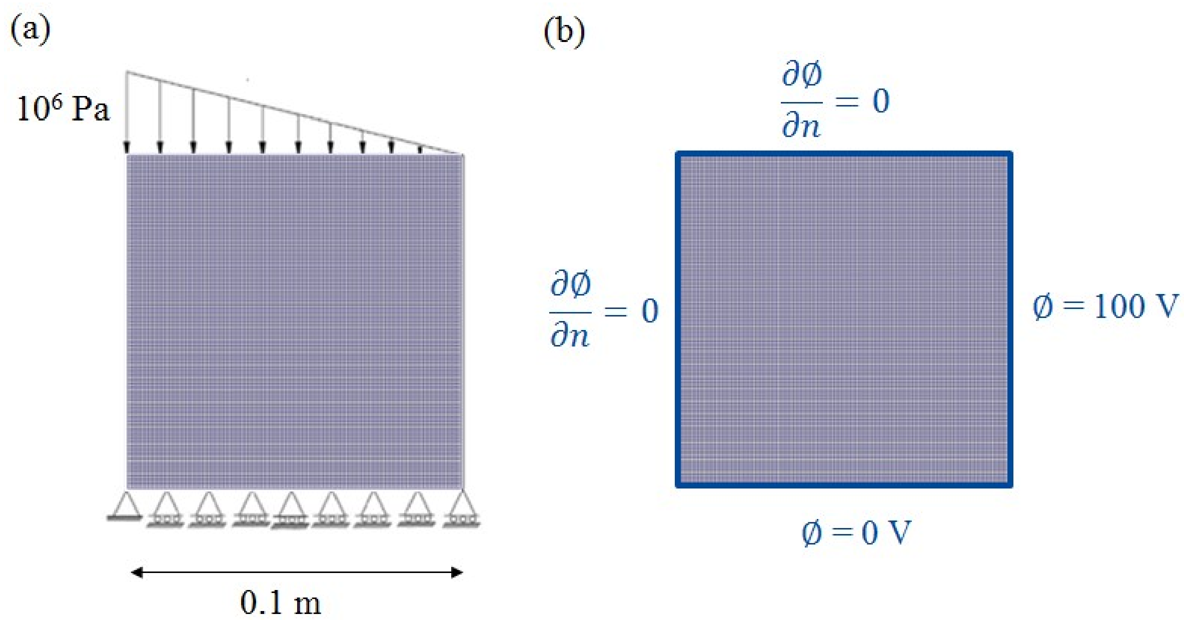

Fig. 1 Meshed FE model of the 2D plate model with boundary conditions relating to bone remodelling: **a** mechanical and **b** electrical (Ø indicates voltage) (Bansod et al. 2019)

For mechanical boundary conditions, the plate was assumed to be fixed on its lower horizontal boundary with the left-most node completely clamped, whereas the rest of the nodes on this boundary have only their vertical displacement constrained (see Fig 1a). The plate is being acted upon by a linearly increasing compressive load on its top boundary with maximum magnitude of 10^6 Pa. For electrical boundary conditions, the potential difference was imposed at the plate boundaries. A voltage of 100 V was placed on the right side and no voltage at the bottom (see Fig 1b). In the remaining contours, the null Neumann condition was applied. Similar to (Alvarado et al. 2012), simulations were performed at a frequency of f = 50 kHz, and with variation in the electrical constant k_{elect} that defines the conversion rate of bone remodelling dependent on the electrical potential.

Flowchart of the implemented algorithm

The main features of this model are briefly summarized below. The electro-mechanical model involves both mechanical and electrical stimuli that can be written, hypothetically, as follows:

$$\frac{d\rho}{dt} = g_m(\rho, W_m(\rho)) + g_e\left(\rho, W_e(\varepsilon(\rho, f))\right) \tag{1}$$

where g_m represents the mechanical stimulus function and g_e is the electrical stimulus. The mechanical strain energy is given by:

$$W_m(\rho) = \frac{1}{2\rho}\lambda^n \, \boldsymbol{\epsilon}^{\boldsymbol{T}} \boldsymbol{C}_{\boldsymbol{0}} \, \boldsymbol{\epsilon} \tag{2}$$

where $C_{\underline{0}}$ is the matrix of linear elasticity with constant coefficients, ϵ is the strain tensor, and ϵ^T represents its transpose. The electrical energy is given by:

$$W_e(\varepsilon(\rho, f)) = \frac{1}{2\rho}\varepsilon(\rho, f) \, \boldsymbol{E}(x, y, z, t)^2 \tag{3}$$

where *E(x,y,z,t)* represents the electric field and *ε(ρ,f)* is the electric permittivity depending on the density and the frequency. It is given by:

$$\varepsilon(\rho, f) = \epsilon_0 \, (B\rho^m + \delta(f)) \tag{4}$$

where *B* is constant, *m* is the density relationship, and *δ(f)* is the frequency function which is applied to the electric field. Additional details of this model can be found in Alvarado et al. (2012). A schematic illustration of the implemented algorithm is presented in Fig. 2.

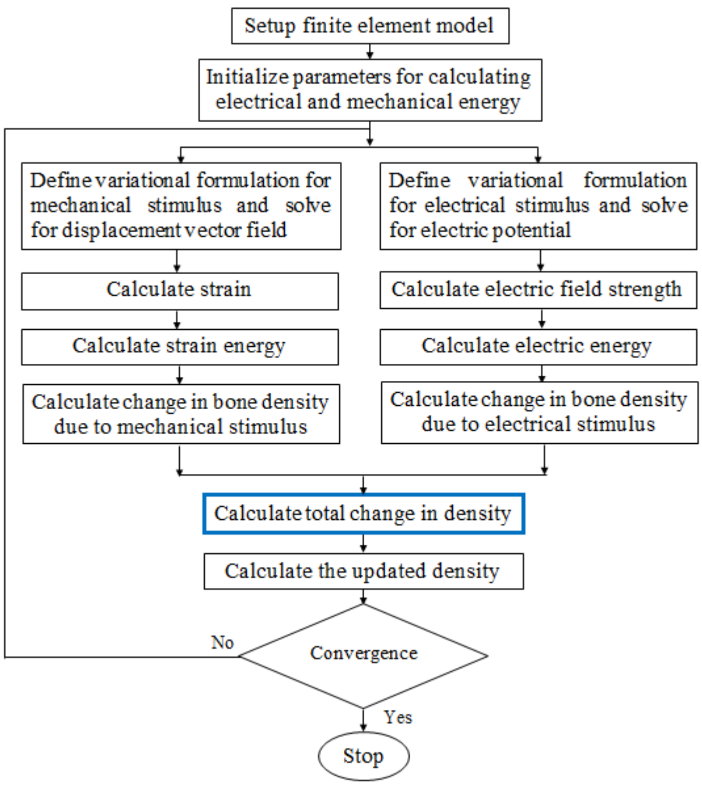

Fig. 2 Schematic representation of the electro-mechanically driven bone remodelling

Here, the bone mass density variation over time depends on the electrical and mechanical stimuli that exist at each spatial point of the bone. This model demonstrated that mass distribution is altered under electrical stimulation, generally resulting in greater deposition of mass.

Proposed open-source framework

Figure 3 represents a flow diagram of the main simulation steps executed using the proposed open-source software framework and more details can be found in Bansod et al. (2019).

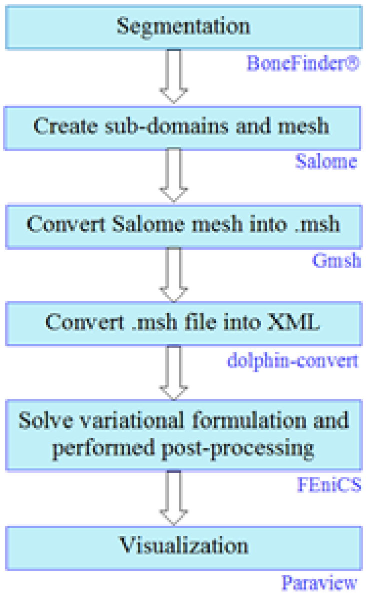

Fig. 3 Open-source software framework used for bone remodelling simulations

The Python scripts and other files created for this study are available for open access on the GitHub repository (https://github.com/YDBansod/Bone_Remodelling).

Comparing obtained simulation results with those from the literature

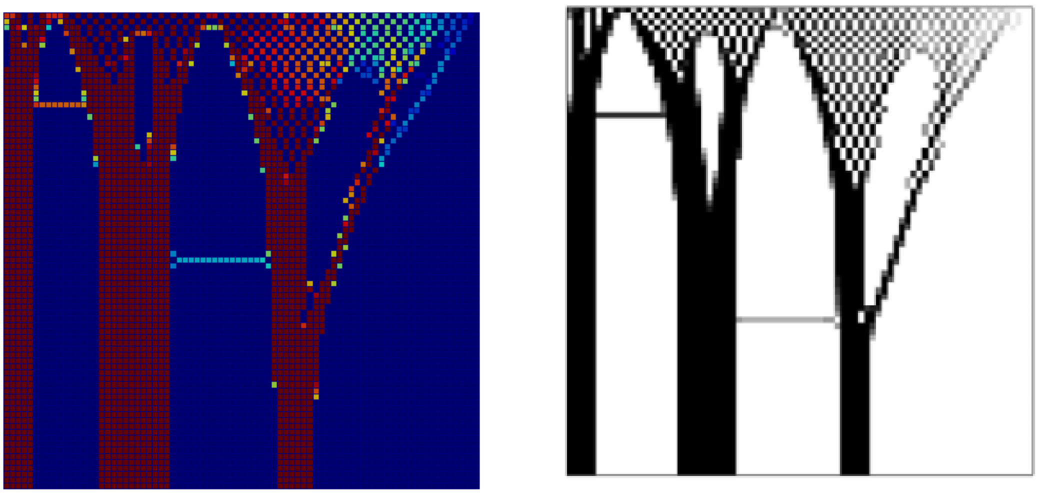

Fig. 4 Density distribution obtained for $k_{elect} = 0.0$ (i.e. mechanical stimulus only) and the corresponding results from Alvarado et al. (2012) (please see Fig 8a on pg -12)

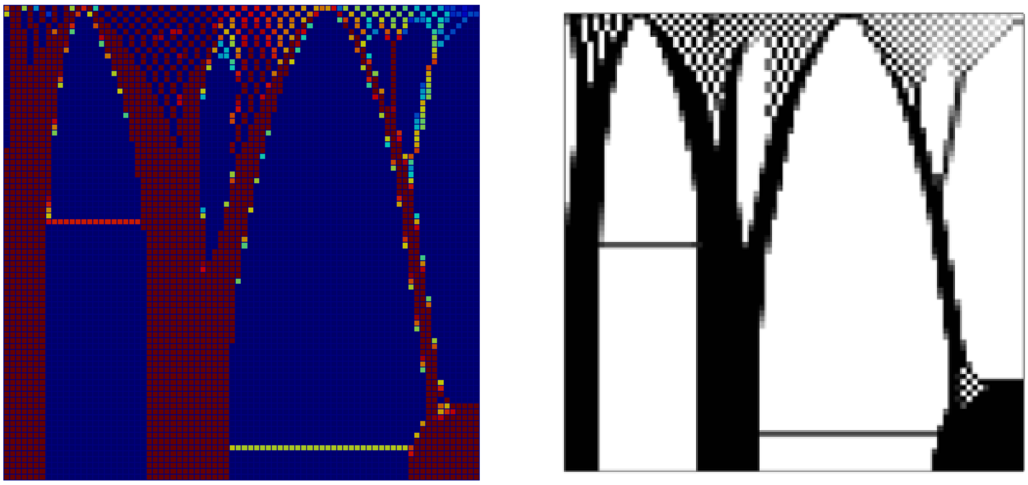

Fig. 5 Density distribution obtained for $k_{elect} = 1.4x10^8$ (i.e. both mechanical and electrical stimulus) and the corresponding results from Alvarado et al. (2012) (please see Fig. 8e on pg -12)

It is evident that the predicted density distributions (see Figs. 4 and 5) are in good agreement with the results of Alvarado et al. (2012). This serves as a preliminary validation of the bone remodelling simulations performed using the proposed open-source framework shown in Fig 3.

References

Garzón-Alvarado DA, Ramírez-Martínez A, Martínez C (2012) Numerical test concerning bone mass apposition under electrical and mechanical stimulus. Theor Biol Med Model 9:14. http://dx.doi.org/10.1186/1742-4682-9-14

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