Mechanical Stimulation of Secondary Bone Healing

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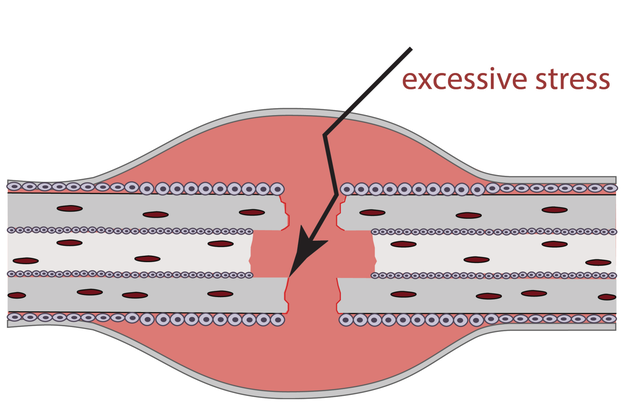
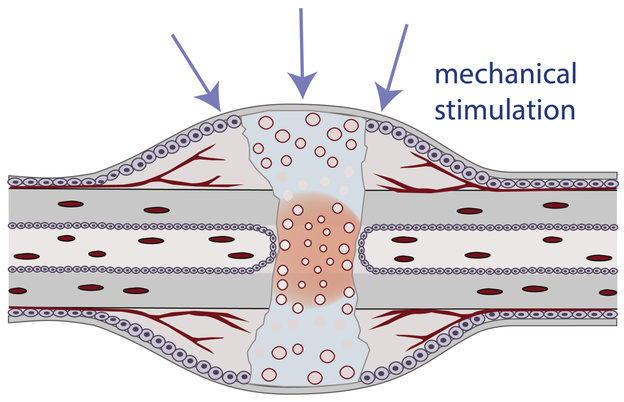
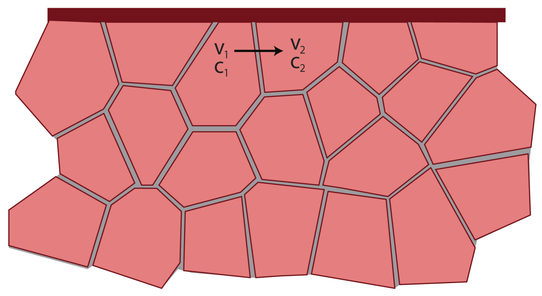
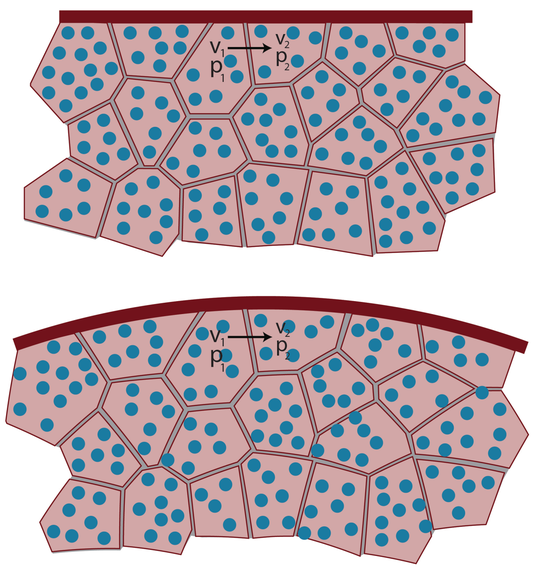
Introduction

Bone can show a remarkable capacity for self-repair under flexible fixation conditions. For instance, fracture healing in the diaphysis of long bones, such as the tibia, occurs with the formation of a callus in what is known as secondary healing. Introducing a local mechanical stimulus within the developing callus tissue can influence cellular differentiation, tissue turnover, and hence improve the rate of healing.







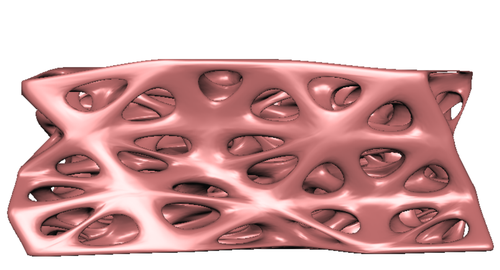


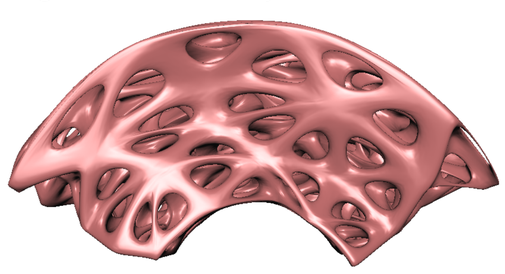
In this work, we investigate the mechanical stimuli driving tissue development during secondary bone healing to optimise clinical treatment of bone fractures. The main aim is to examine to which extent a basic mechanobiological model can explain the local development of different soft tissue types (by means of nutrient transportation through cartilages) in a fracture site during bone healing.

Computational Modelling Of Secondary Bone Healing

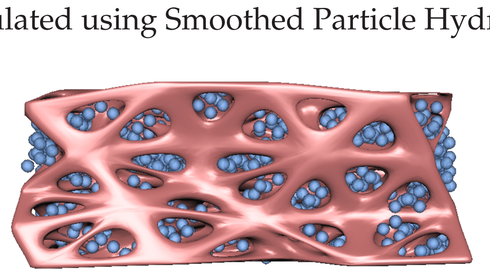
The materials used by the body to repair the fracture via secondary healing are bone, cartilage and soft tissue. These tissues consist mainly of cells forming an intercellular matrix which contains a system of fibres and interstitial fluid.

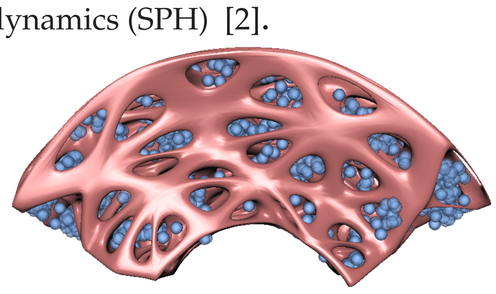
Modelling Cells and Tissues: The cellular structure of the soft tissues is made of an interconnected network of solid struts or plates, which form the cell's edges and faces. To adapt the tissue's material properties (determined by the different material volume fractions, and distributions across the fracture callus). The tissues are simulated as elastic materials using Strain Based Dynamics [1].





Fluid Flow: The cellular materials of the tissues are modelled as permeable to fluid flow, while fluid flow is allowed to occur across borders of the model to imitate the continuity of the callus. Mechanical stimuli produce relatively small pore pressures on the tissue, which cause shear deformation, as well as volumetric deformation, which is expected to increase fluid flows in the fracture site. fluid is simulated using Smoothed Particle Hydrodynamics (SPH) [2].





Simulation Techniques: Coupling Elastic Tissues with SPH Fluids

Strain Based Dynamics:

- We use Position Based Dynamics (PBD) [3] to constrain the entries of the strain tensor.
- Green-St.Venant strain tensor is modified by PBD. This is also known as Green's rotation-independent strain tensor, where the deformation gradient F and Green-St Venant strain tensor G are defined as the following:

$$\mathbf{F} = \mathbf{P}\mathbf{Q}^{-1} \tag{1}$$

, where $\mathbf{Q}$ is material positions and $\mathbf{P}$ is the corresponding world positions.

$$\mathbf{G} = \mathbf{F}^T\mathbf{F} - \mathbf{I} \tag{2}$$

- The diagonal constraints can be solved in a single step, while the off-diagonal constraints decouple stretch from shear resistance.

Smoothed Particle Hydrodynamics (SPH):

- SPH is a meshfree, Lagrangian, particle-based method.
- Navier-Stokes equations govern the conservation of momentum, while the continuity equation states the conservation of mass.

$$\frac{d\mathbf{u}}{dt} = \frac{1}{\rho}\left(-\nabla p + \nabla \cdot (2\mu\mathbf{D})\right) + \mathbf{f}^B \tag{3}$$

, where $\mathbf{u}$ is the velocity, p is the pressure, ρ and μ are the density and coefficient of viscosity of the fluid, respectively. $\mathbf{D} = (\nabla\mathbf{u} + \nabla\mathbf{u}^T)/2$ is the deformation rate tensor, $\mathbf{f}^B$ is the body force per unit mass on the fluid element and t is the time.

- The mass conservation equation for incompressible flows is given by,

$$\nabla \cdot \mathbf{u} = 0 \tag{4}$$

Preliminary Results

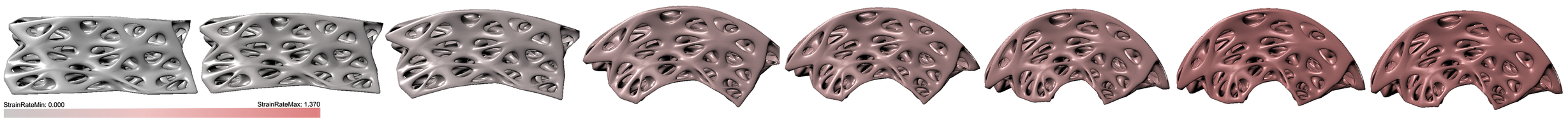


Fig. Deformation Rate: this figure illustrates a representation of the rest position, and shows the seven increasing levels of strain deformation ranging from 0.000 to 1.370.

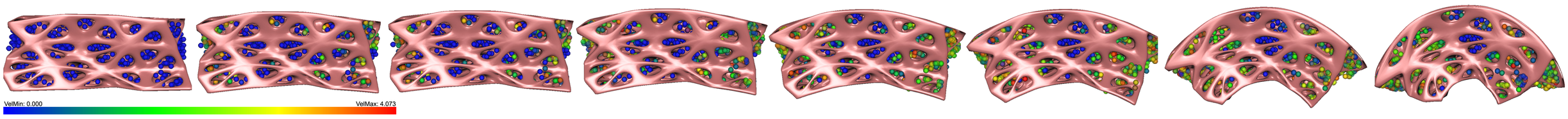


Fig. Flux Velocity: the figure illustrates a fluid particles' velocity during the soft tissues deformation, and shows the diffusion of the fluids within the tissues. In the secondary bone healing process, this flux allows nutrient transportation through cartilages, which influences the healing process significantly.

References

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[3] M.Müller, B.Heidelberger, M. Hennix, J. Ratcliff, Position based dynamics In *Virtual Reality Interactions and Physical Simulation "VRIPHYS" '06*