Simulating bone adaptation and fracture in racehorses' bones.

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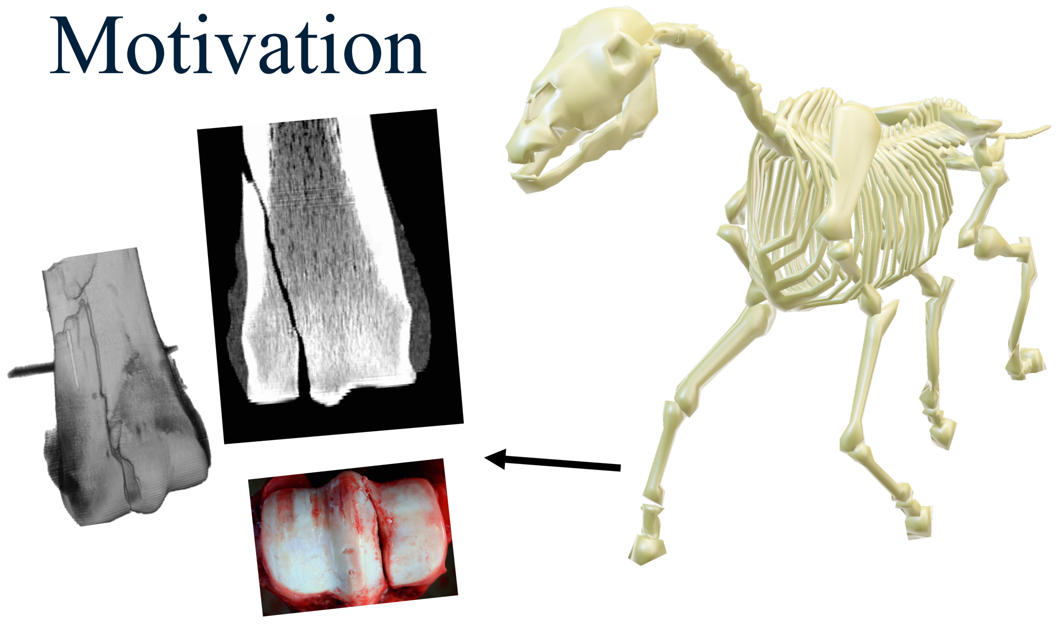
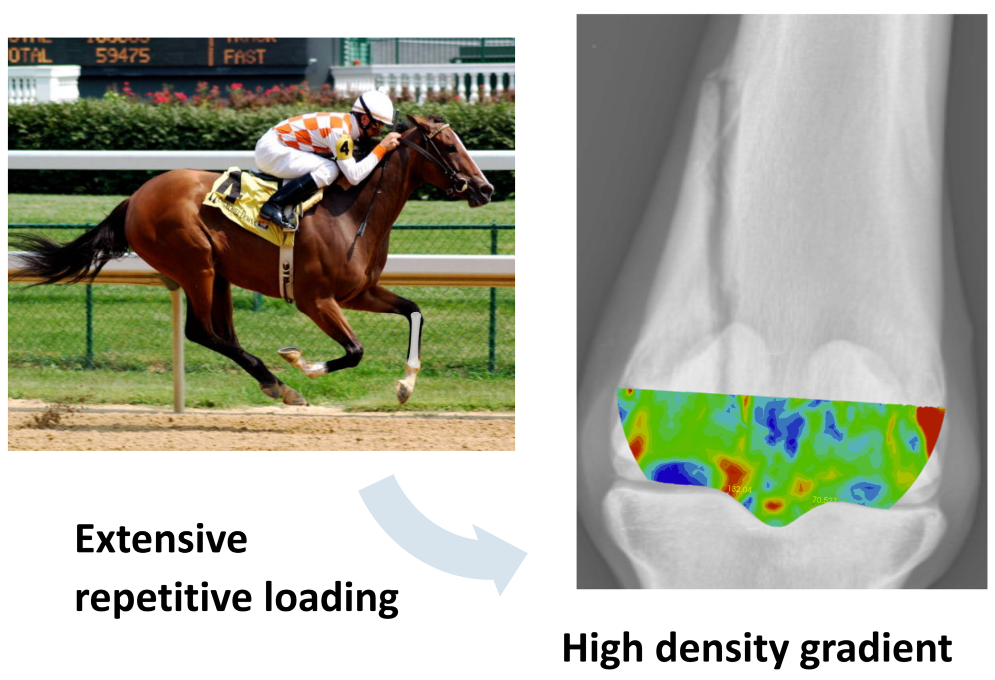
Motivation



Third metacarpal bone (MCIII) fracture has a massive welfare and economic impact on horse racing, representing **45% of all fatal lower limb fractures**, which in themselves represent more than **80% of reasons for death** or euthanasia on racetracks.



The goal of this study is to explore the potential of advanced computational models to predict bone density and subsequently estimate bone's propensity for fracture.

Methods

The bone remodelling/adaptation is simulated with phenomenological model proposed by Ellen Kuhl and Paul Steinmann (2003).

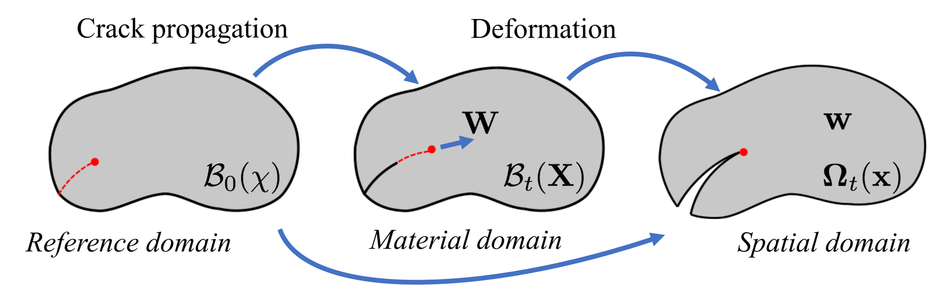
Balance equations

Conservation of mass:
$$\frac{\partial \rho}{\partial t} = R_0$$

Conservation of momentum:
$$\rho \frac{\partial v}{\partial t} = \mathrm{Div}\,\mathbf{P}$$

Constitutive equation:
$$R_0 = c\left[\left[\frac{\rho_0}{\rho_0^*}\right]^{n-m} \psi_0^{\mathrm{neo}} - \psi_0^*\right]$$

The numerical analysis of crack propagation in heterogeneous materials is studied within the framework of configurational mechanics.

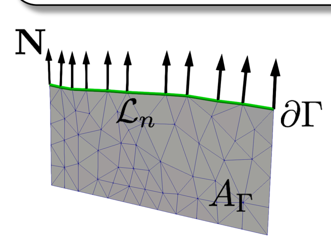


1st Law of thermodynamics

Crack front equilibrium:
$$\mathbf{W}\cdot(\gamma\mathbf{A} - \mathbf{G}) = 0$$

2nd Law of thermodynamics

Crack evolution direction:
$$\mathcal{D} = \gamma\dot{\mathbf{W}}\cdot\mathbf{A}_{\partial\Gamma} \geq 0$$



Criterion for crack growth (Griffith):
$$\phi(\mathbf{G}) = \mathbf{G}\cdot\mathbf{A}_{\partial\Gamma} - g_c/2 \leq 0$$

Configurational (driving) force:
$$\mathbf{G} = \lim_{|\mathcal{L}|\to 0}\int_{\mathcal{L}_n} \Sigma\mathbf{N} + \mathbf{f}^{\mathrm{inh}}\,\mathrm{d}L$$

Material resistance:
$$\gamma\mathbf{A}_{\partial\Gamma}$$

The crack front position is determined implicitly by equilibrium condition. Subsequently mesh nodes are moved to resolve the new crack geometry.

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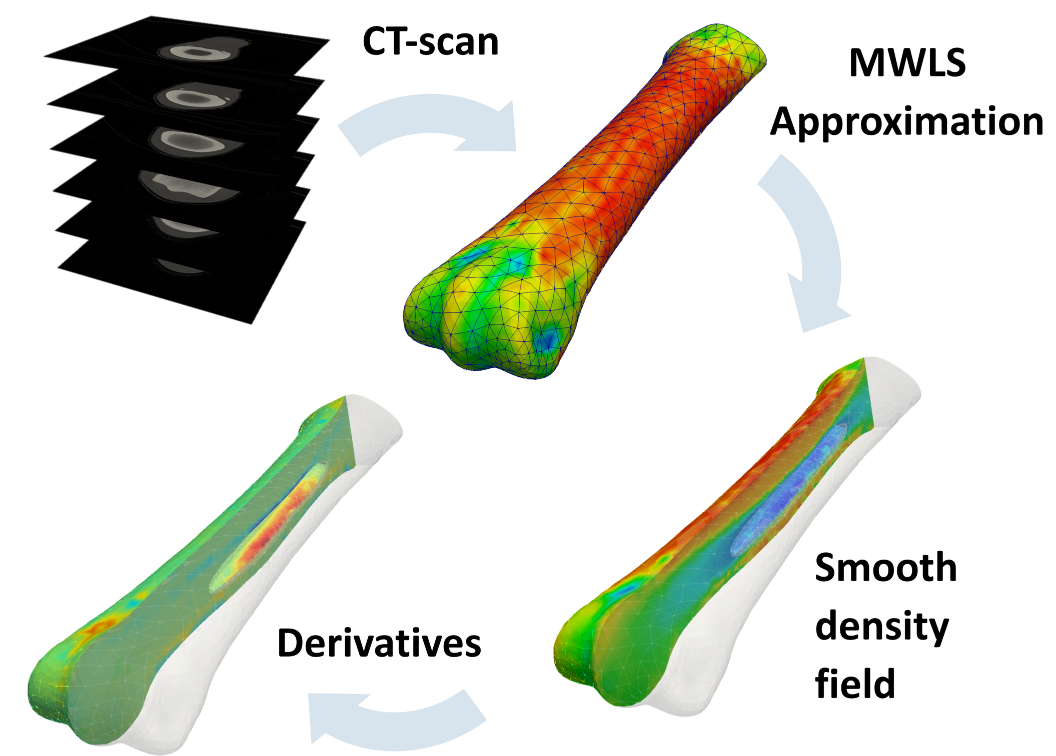
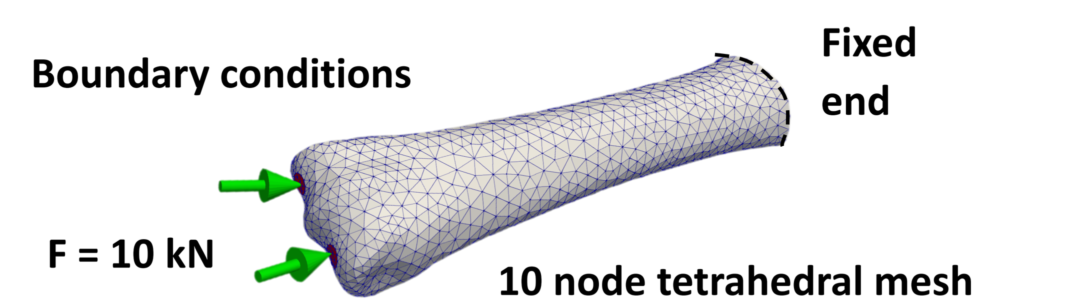
A computational model of MCIII bone was generated by processing CT-scan images. Density was incorporated in the model using a dipotassium phosphate (K_2HPO_4) phantoms.

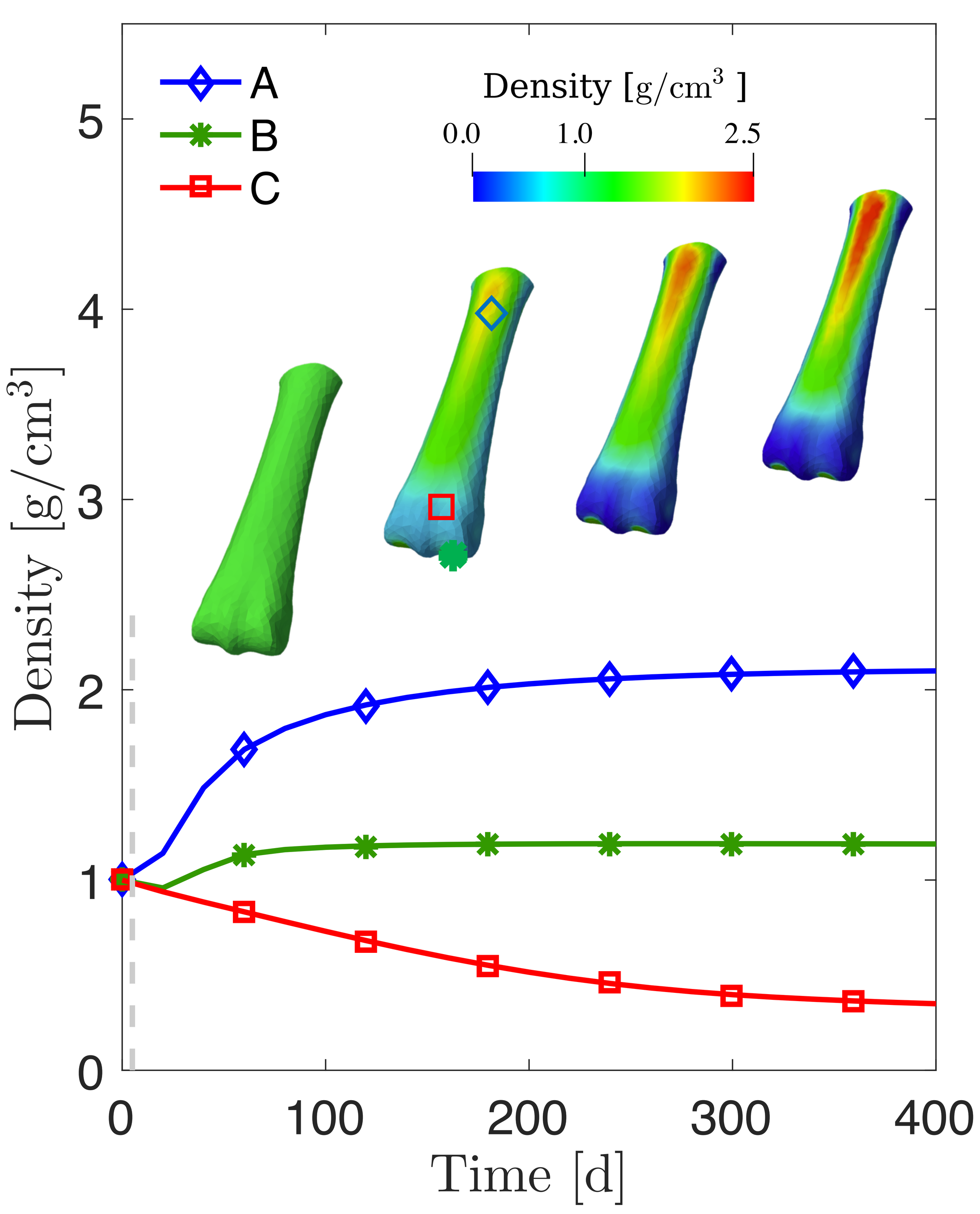


Finite element model used for bone remodelling and fracture analyses.



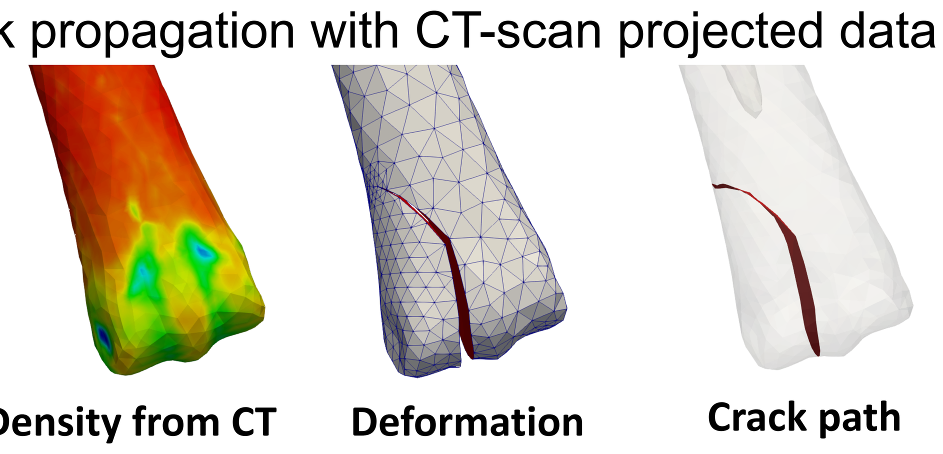
Results

A 3D finite element finite element analysis of bone remodelling for equine MCIII revealed increased bone density on the articular surface (**B**) and the cortical shaft (**A**).



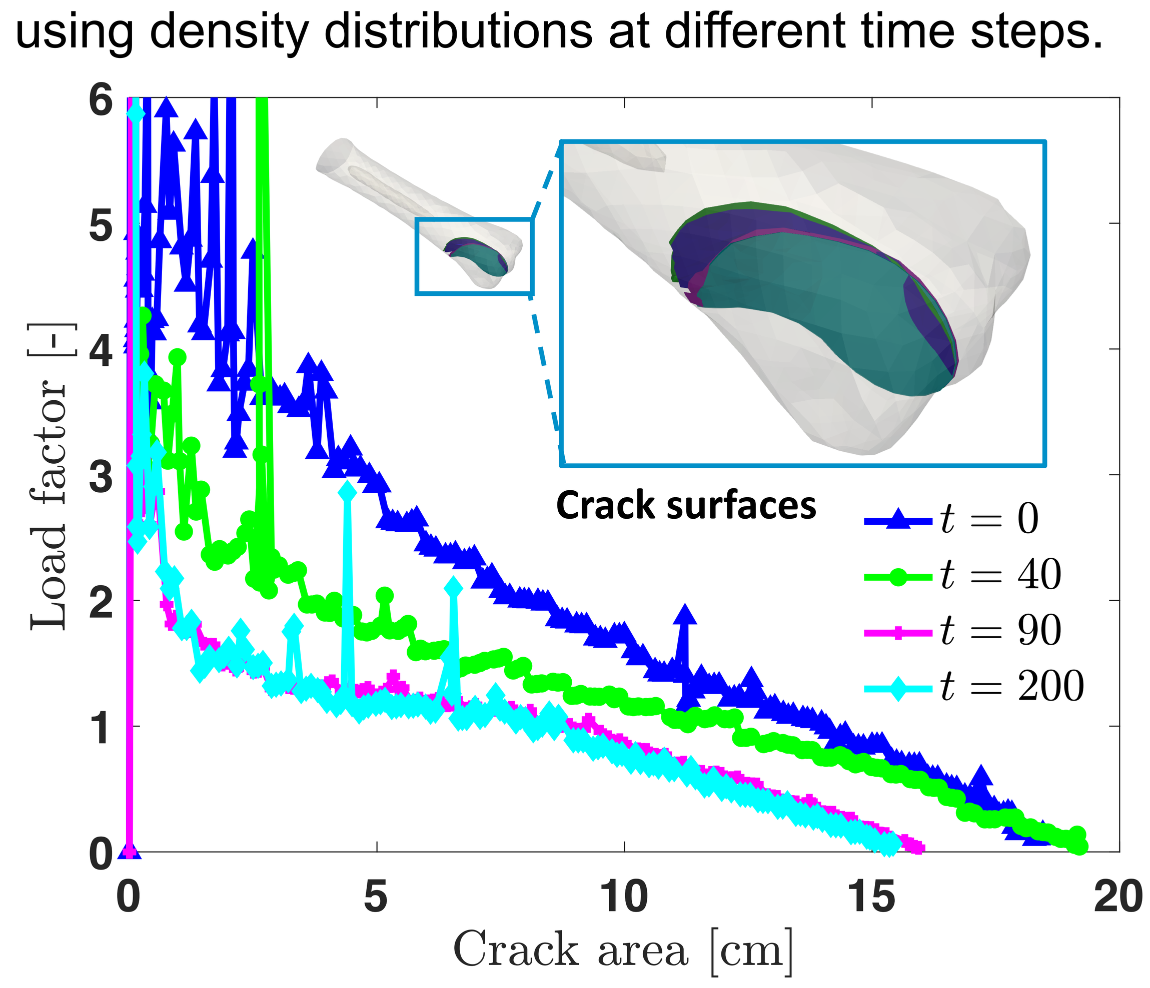
Simulated density evolution over time.

Crack propagation with CT-scan projected data



The simulated crack path is in good agreement with fractures observed on radiographs.

On the previous results from remodelling analysis crack propagation simulation has been performed using density distributions at different time steps.

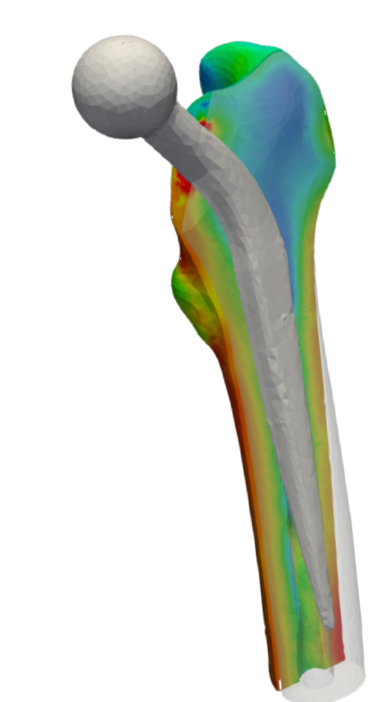


The differences in load factors between time steps indicate increase in fracture propensity over time due to applied loading (training regime).

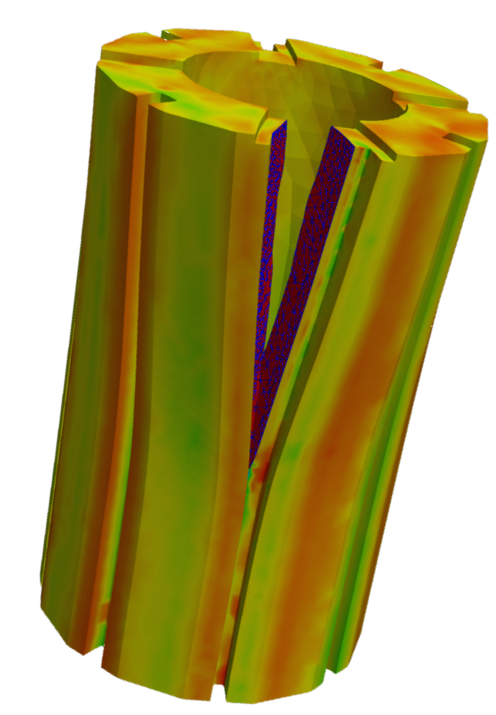
Discussion

The results of this study could be of benefit to high performance equine athletes and patients with other bone degenerative issues, such as bone loss by astronauts in microgravity. In the future, models to determine improved training strategies could be developed to prevent fatal injuries. Moreover, with the extensive validation it is possible to extend the model for more complex problems.

Simulation of crack propagation in heterogeneous materials can be also of interest in industrial applications.



Stress shielding after total hip replacement surgery.



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