Fracture Healing Rate Depends on Morphology in Mechanoregulation Models

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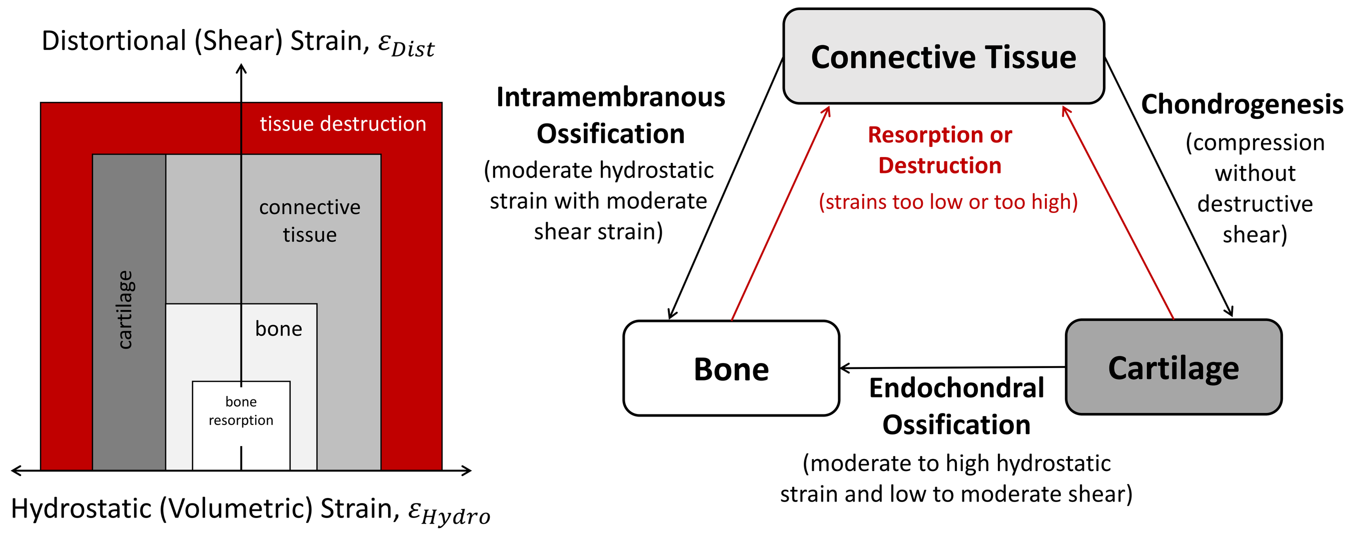
Summary

Fracture healing simulations with strain-based mechanoregulation rules suggest that fracture morphology influences the interfragmentary strain environment and the speed of secondary bone healing.

Introduction

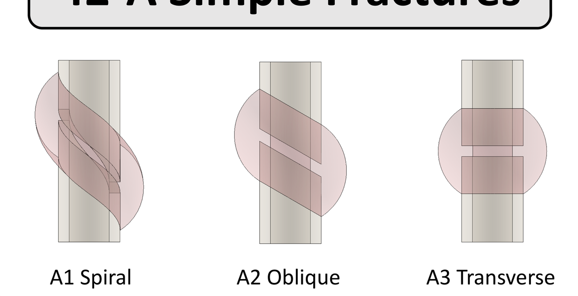
Secondary bone healing is a mechanoresponsive process that is controlled by the local mechanical conditions within the healing zone. Computational models have been successfully used to simulate this process with strain-based fuzzy logic rules for tissue differentiation[1,2].



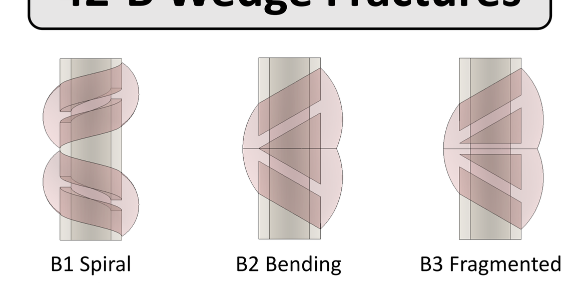
$$\varepsilon_{Hydro} = \frac{1}{3}(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}) \qquad \varepsilon_{Dist} = \frac{2}{3}\sqrt{(\varepsilon_{11} - \varepsilon_{22})^2 + (\varepsilon_{22} - \varepsilon_{33})^2 + (\varepsilon_{33} - \varepsilon_{11})^2 + 6(\varepsilon_{12}^2 + \varepsilon_{23}^2 + \varepsilon_{31}^2)}$$

In the past, these algorithms have been applied to axisymmetric simple transverse fracture models[3]. In contrast, clinical data suggests that fracture morphology (i.e. AO/OTA type) may be associated with differences in healing outcomes, independent of soft tissue injury severity. Idealized model renderings of AO/OTA 42-A/B/C diaphyseal tibial fractures are shown here.

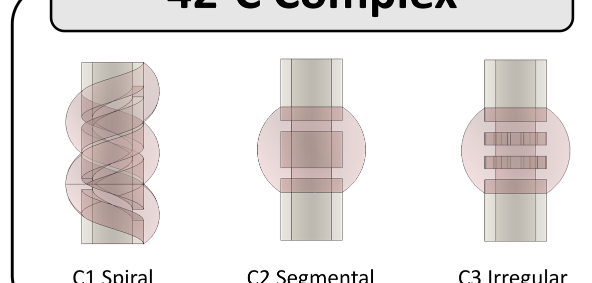
42-A Simple Fractures



42-B Wedge Fractures



42-C Complex



In this study, we carried out mechanoregulation fracture healing simulations on a variety of idealized AO/OTA 42 fractures.

The hypothesis of this study was that fracture morphology can significantly influence interfragmentary strains and as a result, cause differences in healing speed.

Selected References:

1. Shefelbine SJ, Augat P, Claes L, Simon U. Trabecular bone fracture healing simulation with finite element analysis and fuzzy logic. *J Biomech*. 2005;38(12):2440-2450.
2. Ament C, Hofer E. A fuzzy logic model of fracture healing. *J Biomech*. 2000;33(8):961-968.
3. Steiner M, Claes L, Ignatius A, Simon U, Wehner T. Numerical simulation of callus healing for optimization of fracture fixation stiffness. *PLoS One*. 2014;9(7):1-11.

Methodology

Fracture Geometry Modeling in SOLIDWORKS

- Models created to match the AO/OTA classification of tibial fractures (42-A/B/C)
- Axisymmetric cortical shaft segments (length, L = 50 mm, diameter, D = 17 mm)
- Normal healing modeling with 3-mm axial fracture gap distance
- Consistent callus body volume (7500 mm^3) in all geometries

Structural Mechanics Simulations in ANSYS Workbench

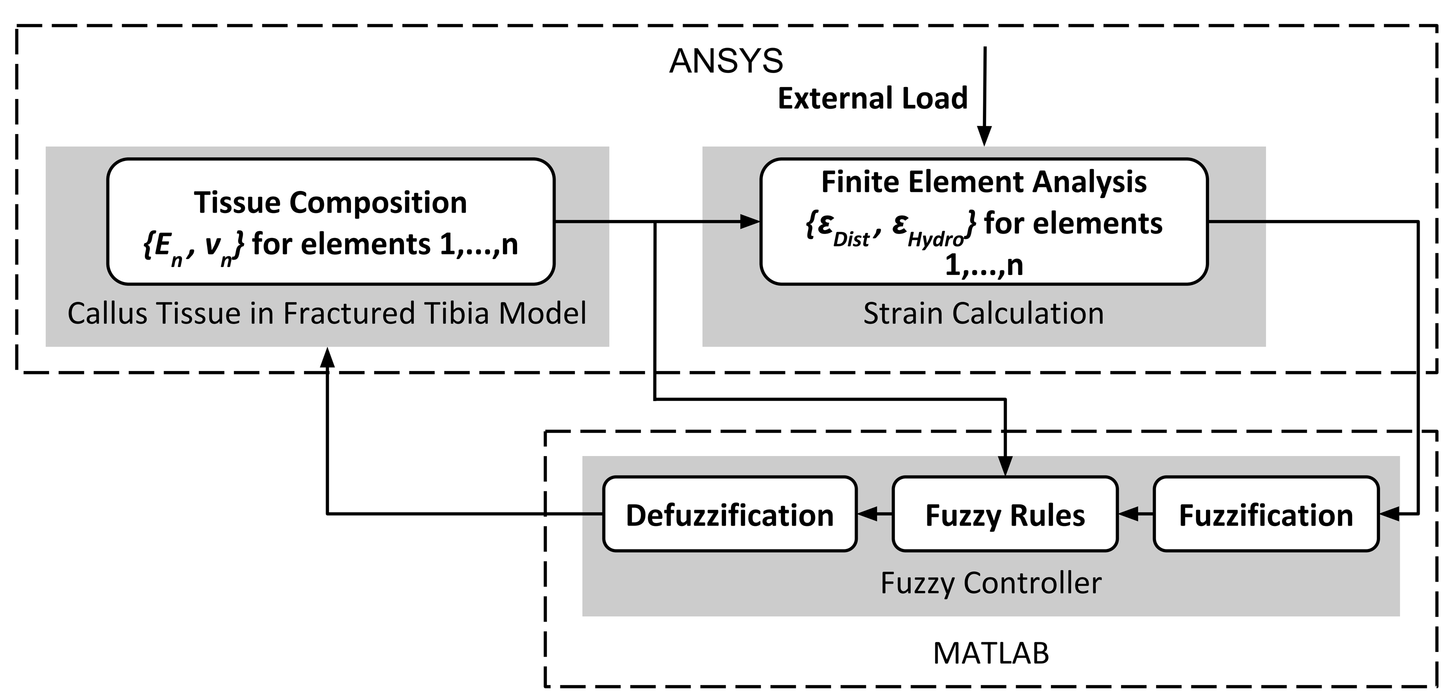
- Model for intramedullary nail fixation: nonlinear spring with 0.2 mm of free axial compression (screws/hole clearance in the implant construct) followed by a linear stiffness of 2650 N/mm (tibial nail with four bone screws)
- Linear elastic isotropic material properties for each tissue type based on published methods[2].
- Automatic mixed-element meshing and mesh refinement
- Proximal fragment 160 N applied load (partial weight bearing)

Callus Tissue Type	E [MPa]	ν [-]
Woven Bone	4,000	0.30
Cartilage	40	0.35
Connective Tissue	0.5	0.45

- Model initialized to 100% connective tissue in callus zone. Iterations continued until models achieved $\leq$ 5% change in torsional rigidity in a simulated torsion test: $R_{tor} = ML/\phi$ [Nm^2/deg]

Fuzzy Logic Mechanoregulation Model in MATLAB

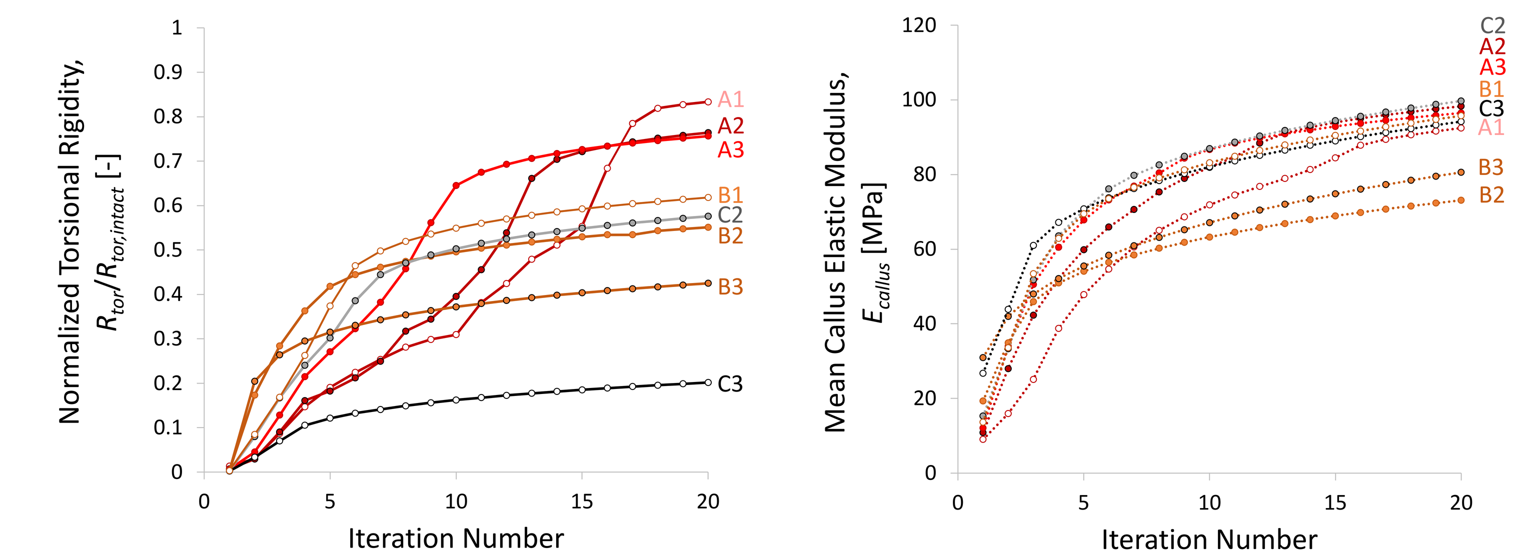
- At each iteration, element-wise tissue type ratios and distortional and hydrostatic strains were exported for entire callus zone.
- Differentiation (tissue type evolution) controlled by Fuzzy Logic Toolbox
- Rule of mixtures applied to update element-wise mechanical properties in ANSYS



Results and Discussion

Callus Maturation in the Early Healing Period

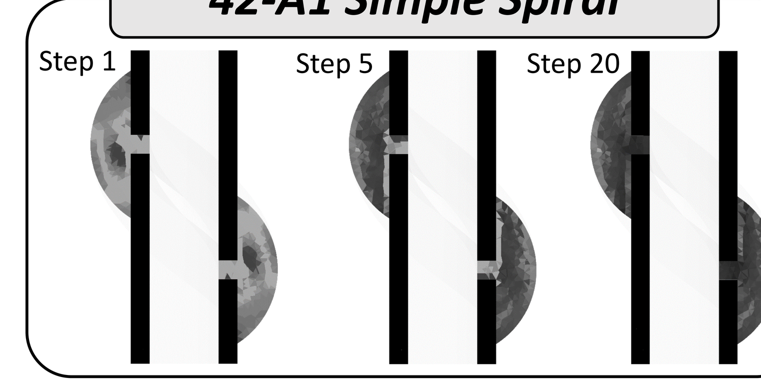
- A simulated torsion test after each axially-driven tissue differentiation cycle produced bone/callus torsional rigidity, R_{tor}, normalized to intact cortical bone
- Callus mean elastic modulus was calculated using a proportional rule of mixtures for properties in each element



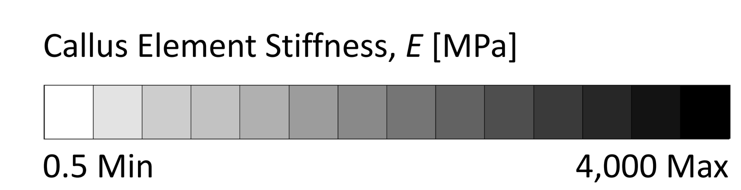
- Bending and fragmented wedge (B2, B3) fractures had the highest initial rate of increase in torsional rigidity but persistent instability.
- Simple fracture patterns (A1/2/3) had lower initial rates of increase in torsional rigidity but highest end-point rigidity (greatest stability).
- Models with floating bone fragments (B3, C3) healed most slowly.
- Clinically relevant fracture stability is determined by both the percentage of new bone (average E) and morphology (AO/OTA classification)

Tissue Type Localization and Callus Bridging

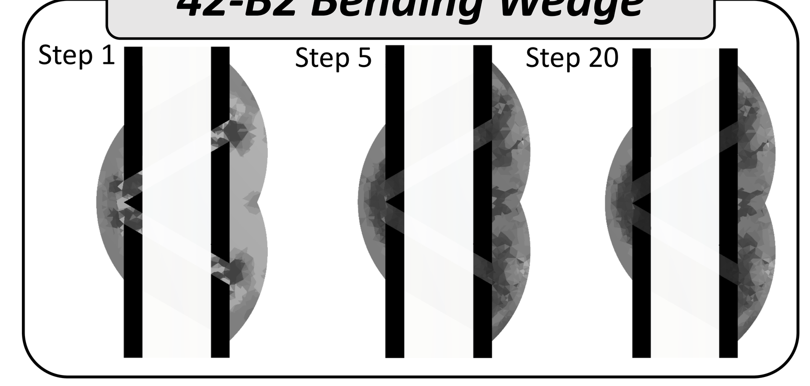
42-A1 Simple Spiral



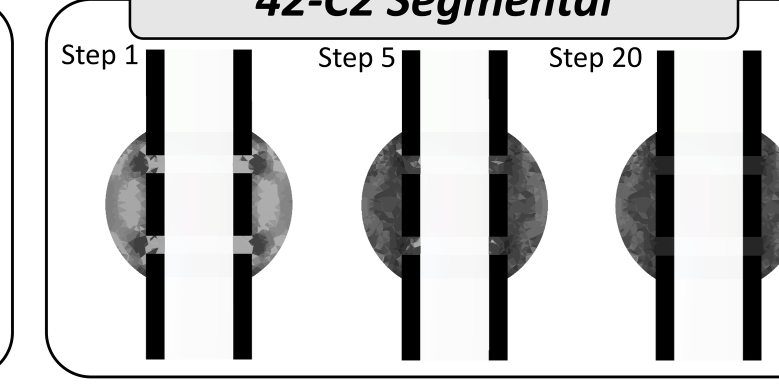
- In all models, stiffening occurred in the external bridging callus first and interfragmentary gap later.



42-B2 Bending Wedge



42-C2 Segmental



Conclusions & Clinical Takeaways

Given the same load conditions and mechanoregulated healing rules, different AO/OTA fracture types may have very different rates of early healing, independent of other factors such as soft tissue injury severity.

Future studies should address the need for tailored implant design and postoperative weight bearing instructions based on inherent the inherent mechanical stability of different fracture types.

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