

CHARACTERIZATION OF THE MECHANICAL ENVIRONMENT IN THE FRACTURE CALLUS DURING AXIAL COMPRESSION LOADING OF OSTEOTOMIZED MICE TIBIA

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Applying a mechanical load to healing bones may enhance or inhibit successful fracture repair;¹⁻² however, specific loading conditions that lead to enhanced fracture repair are unknown. Parameters such as the load magnitude, frequency, duration, and the delay between fracture and beginning a loading regimen have each been shown to have significant effects on the healing process.³ Finite element models (FEM) provide quantitative stress and strain magnitudes that are valuable in determining parameters for successful fracture repair, and that are experimentally unobtainable. Two-dimensional FEMs used in previous studies do not accurately model the complex forces produced in the fracture callus during mechanical loading.⁴ The goal of this study was to characterize the local mechanical environment inside the fracture callus during axial compression loading using a three-dimensional (3D) FEM and to correlate these analytical results with experimental data.

A 3D FEM was created by combining two individual models: one of the tibia and one of the fracture callus. The tibia model was created directly from microCT images of a mouse tibia. The callus model was generated from a set of nine cross sections taken from microCT (Geomagic Studio 4.0) images near the osteotomized part of the tibia that were manipulated to model the callus geometry. A mesh was created for each of the models and the models were integrated, forming the final model that contained 23,392 nodes (TrueGrid). The elastic modulus of cortical bone was 28.3 GPa, the fracture gap had an elastic modulus of 3 MPa, and the callus elastic modulus was defined as 1.0 GPa, 3.0 GPa, or 6.0 GPa to model soft, intermediate, or hard callus, respectively. Cortical bone and the callus had a Poisson Ratio of 0.3, and the fracture gap had a Poisson Ratio of 0.4. The proximal end of the model was kept immobile, while the distal end was free to move in any direction. Loads of 1N, 2N, or 4N, correlating with maximum load magnitudes from the experimental study, were applied along the long axis of the bone. Axial stress and strain, as well as von Mises and hydrostatic stress, were used to assess the mechanical environment of the fracture callus (Patran). The local tissue bone mineral density (tBMD) for the posterior and anterior side of the fracture callus was also quantified using the microCT images (MicroView).

Mechanical loads applied to the distal end of the tibia produced both tensile and compressive forces within the bone and callus due to curvature of the tibia and the asymmetric geometry of the fracture callus. Loading produced compressive axial stresses and strains in the posterior side of the callus and tensile axial strains in the anterior side of the callus. For a 1N load magnitude and a callus modulus of 1.0 GPa, the hydrostatic stress in the callus ranged from -0.56 to 0.94 MPa and axial strains in the callus ranged from -2450 to 970 $\mu\epsilon$. The magnitude of the load applied during fracture healing had a much more significant effect on the local mechanical environment of the fracture callus than did the material properties of the callus. Stress and strain magnitudes scaled linearly with the maximum applied load, but were higher posteriorly than anteriorly. Increasing the elastic modulus of the callus from 1.0 to 6.0 GPa decreased the maximum hydrostatic stress in the callus only by 7.4%, but significantly decreased the maximum axial strain (79.6%). Bending moments were also found to be acting on the ends of the callus. A 1N axial load created bending moments in the anterior-posterior plane and medial-lateral plane of 3.27 N·mm and 2.28 N·mm, respectively. The lowest stresses and strains were observed periosteally and near the periphery of the callus, with the highest stresses observed endosteally near the fracture gap. The highest strains were located in the fracture gap due to the low elastic modulus in this region. The results of the microCT analysis found that the posterior (compressive) side had a significantly higher tBMD than the anterior (tensile) side of the same bone ($p = 0.05$).

Using the experimental data, a load magnitude equal to about 1.5 times the body weight applied four days post-operatively produced hydrostatic stress magnitudes below 1 MPa and axial strain below 1000 $\mu\epsilon$, and were osteogenic. Larger load magnitudes produced stress and strain magnitudes that did not enhance healing. Local stress and strain distributions explain localized density differences in the fracture callus. Compressive forces produced a higher tBMD locally in the fracture callus than did tensile forces, suggesting compression is more osteogenic. The bending moments found to be acting on the fracture callus suggest 3D FEMs provide better physiological loading models compared to 2D models.

References:

1. Goodship and Kenwright (1985). *British Editorial Soc of Bone and Joint Surg.* 67B: 650-5
2. Wolf, et al. (1981). *J Bone and Joint Surg.* 63: 805-810.
3. Bailon-Plaza and van der Meulen (2003). *J Biomech.* 36: 1069-1077
4. Carter, et al. (1998). *Cinical Ortho Related Res.* 355S: 41-55