Comparison of Bending and Torsion in Virtual Mechanical Testing of Preclinical and Clinical Fracture Healing

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INTRODUCTION: In preclinical models of fracture healing, torsional loading is the postmortem mechanical test of choice because it is not sensitive to errors arising from specimen malalignment. Bending loads are arguably more physiologically relevant, but they are highly sensitive to alignment due to the natural variations in the flexural rigidity of intact long bones in different bending directions. For these reasons, our methods for image-based virtual mechanical testing of fracture healing were validated using postmortem physical torsion tests.[1] In a clinical setting, we have used virtual torsion tests to measure human tibial fracture healing under normal healing conditions.[2] In clinically diagnosed tibial nonunions, we previously reported that late-stage oligotrophic and hypertrophic nonunions may develop high torsional rigidity, despite having irregular callus bridging and persistent bone defects at the fracture line. This observation led to a question: Is torsion testing capable of detecting mechanical insufficiency in late-stage nonunion fractures? To answer this question, the technical objectives of the present study were to: 1) develop a methodology for virtually measuring the bending flexural rigidity of fractured long bones using sheep data, and 2) use the same methodology to perform virtual mechanical tests on clinical nonunions and normal healing tibiae. Our hypothesis was that the virtual flexural rigidity (VFR) corresponding to physiologic loading (anterior tension) is strongly correlated with virtual torsional rigidity (VTR).

METHODS: Three datasets were used in this analysis: ovine tibial osteotomies, normally healing human tibial fractures, and late-stage tibial nonunions. The animal and clinical study protocols were reviewed and approved by the ethical committees in each institution. The sheep (N = 24) were all stabilized by medial plating, with osteotomy defect sizes from 3-mm to 17-mm with allograft.[2] Postmortem (9 and 12 weeks) μCT scans were down-sampled to 400 μm isotropic resolution. The normally healing fractures (N = 19, 2 female, 17 male) were prospectively recruited from a single Level I trauma center and CT scanned at 12 weeks post-op.[2] The nonunions (N = 16, 4 female, 12 male) were retrospectively identified at four Level I trauma centers, with scans taken at a median of 1.09 years after initial injury. Clinical scans had an average in-plane resolution of 0.41 mm and average thickness of 1.2 mm. All human data was from patients treated by intramedullary (IM) nailing. Scans were processed in Mimics Innovation Suite (v.23, Materialise Inc.) to reconstruct 3D models of the fractures. Regions of cortical bone and callus were thresholded, volumetrically reconstructed, and meshed with quadratic tetrahedral elements. Voxel-based density scaling was used to assign tissue elastic moduli values in an elementwise fashion.[1,2] Finite element (FE) models were exported to ANSYS Workbench Mechanical (ANSYS Inc.) for virtual mechanical testing. VFR was calculated as VFR $= M\rho$ [N-m^2], where M = 31 N-m is the moment amount applied for the bending test, and ρ is the radius of the curvature of the model during bending testing. Bending direction was set by defining a local reference coordinate system at the proximal end plane. The radius of curvature (ρ) was calculated using a custom MATLAB code that found the line produced by the intersection of the proximal and distal cut surface planes in the deformed model and calculated the distance from this intersection line to the FE model centerline. VTR was calculated as $\mathrm{VTR} = ML/\phi$ [N-m^2/°], where M is the moment reaction calculated in the model, L is the length of the test segment, and ϕ is the torsion test twist angle.

RESULTS: In all FE models, bending generated physiologically relevant anterior tension and posterior compression (**Fig. 1A**). In the ovine osteotomies, VFR was very strongly and significantly correlated with VTR (**Fig. 1B)**. Similarly, in the human fractures, the bending and torsional rigidities were very strongly correlated in the normally healing fractures and strongly correlated in the nonunions (**Fig. 1C**). Compared to normally healing fractures, the late-stage nonunions had more variability (larger range) in both VFR and VTR, but there was no significant difference between the normally healing fractures at 12 weeks and late-stage nonunions in either measure ($p > 0.127$; FVR data shown in **Fig. 1D**).

DISCUSSION: The results of this study demonstrate that although the torsion is not the predominant physiologic mode of loading, it is the ideal simplified mechanical test because it captures variations in bending rigidity related to fracture healing without the challenges of direction-dependency. Compared to virtual bending tests, virtual torsion tests are much easier to set up and the data is easier to interpret. The virtual torsion test has also been robustly validated to experimental data[1] and the results differentiate between good and poor healers across species. These results also confirmed that nonunions can develop structural rigidity despite their irregular bridging pattern and that this diverse mechanical behavior is meaningfully represented in both bending and torsion.

SIGNIFICANCE/CLINICAL RELEVANCE: Image-based virtual torsion tests are strongly recommended for fracture healing assessment because they are reliable, easy to implement, useful in preclinical and clinical settings, and capture wide variations in bone healing.

REFERENCES: [1] Inglis+, *Sci Rep*. 12(1):2492 (2022). [2] Dailey+, *J Bone Jt Surg*, 13(101-A):1193-1202 (2019).

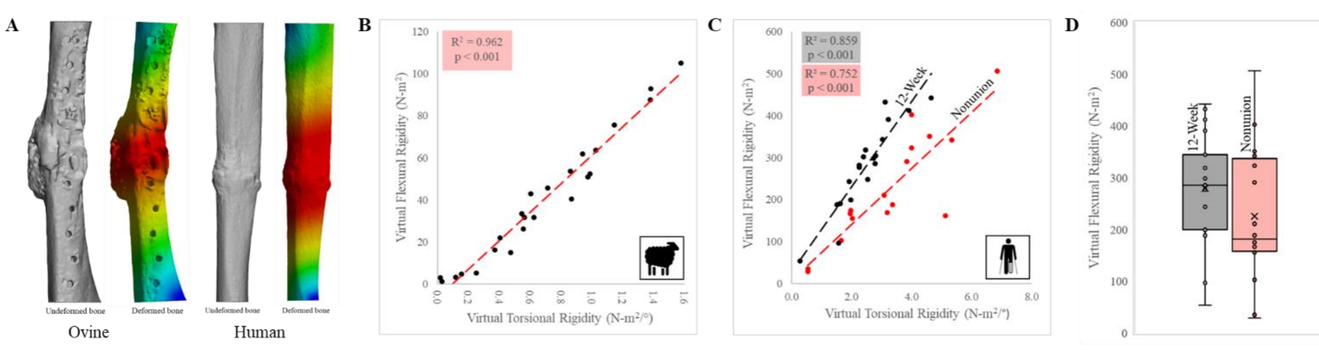

Figure 1 – **A)** Representative FE models of an ovine tibial osteotomy and a human tibial fracture with deformation contours generated in the virtual bending test. **B)** In ovine osteotomies, virtual flexural rigidity (VFR) was very strongly correlated with virtual torsional rigidity (VTR), the measure we previously validated using experimental data. **C)** VFR and VTR were also strongly correlated in human tibiae, both for normally healing fractures and late-stage nonunions. **D)** The distributions of VFR were not significantly different between normally healing and late-stage nonunion fractures ($p = 0.187$).