

The Influence of Disc Elasticity on the Micromechanics of Vertebral Failure for Forward Bending

^{+1,2}Yang, H; ¹Jekir, M G; ¹Ruf, S F; ¹Keaveny, T M

⁺¹University of California, Berkeley, CA, ²Harbin Institute of Technology, Shenzhen, China
haisheng@me.berkeley.edu

Introduction

Wedge fractures are the most common type of osteoporotic spine fractures. In laboratory cadaver studies in which bending loads are applied through a stiff endcap, wedge-shaped fractures are often produced [1], suggesting that this configuration adequately replicates the failure mechanisms that occur *in vivo*. Testing of cadaveric spine motion segments has shown that disc degeneration alters the load sharing between the anterior and posterior halves of the disc [2], suggesting that disc degeneration may directly influence vertebral stresses. However, several questions still remain: is a degenerated disc biomechanically equivalent to a layer of PMMA, in terms of consequences on vertebral strength? What is a typical range of elastic stiffness for a disc? How does variation of disc elasticity affect the failure mechanisms of the vertebra? To address these issues, we used cadaver experiments and high-resolution finite element analysis to measure typical disc elastic stiffness properties and to then study the influence of these properties on the micromechanics of vertebral failure under forward bending.

Materials and Methods

For our cadaver experiments, 16 bone-disc-bone motion segments were disarticulated from nine anonymous donor spines aged 66±16 years. The adjacent vertebrae were hollowed out and filled with PMMA to prevent endplate deformation. Each specimen was compressed to failure at a low strain rate of 0.05%/s or a high strain rate of 20%/s (Figure 1). An effective elastic modulus for the disc was calculated at the point of maximum stiffness from each stress-strain curve. For our finite element analyses, forward bending [2] was virtually applied to a micro-CT based finite element model (60 micron element size; ~50 million elements total) of one T9 vertebra (82 years, male) through a simulated isotropic elastic homogeneous layer of “disc”. In a parameter study, the effective elastic modulus of this disc layer was varied from 8–2500 MPa and separate linearly elastic finite element analyses were performed for each case (n=18 total). For each simulation, the boundary conditions comprised of fixing the bottom surface of the inferior disc layer and rotating the top surface of the superior disc layer by 5° in a sagittal plane about the most superior-posterior point. One outcome was the axial compressive force acting on each half (anterior vs. posterior) of the superior vertebral endplate, and their ratio. To assess failure mechanisms, the top 10% of the most highly loaded elements was defined as the “high-risk” tissue, *i.e.* most likely to fail first.

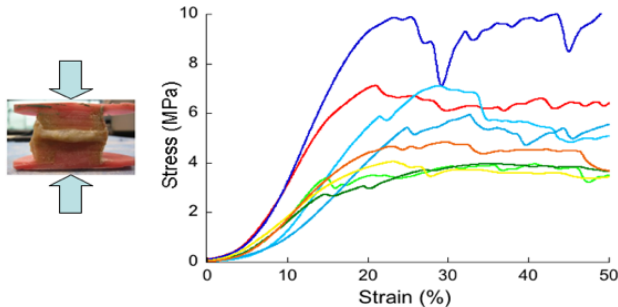


Figure 1. Experimentally-measured stress-strain curves for n=8 discs compressed at a high strain rate.

Results

In our experiment, we measured an effective elastic modulus of the disc in the range of about 5–50 MPa, with strength values ranging from 2.1–10.3 MPa (Figure 1). In our finite element analyses, we found a highly non-linear relation between the forces acting on the endplates and the assumed effective elastic modulus of the disc (Figure 2). Examining spatial distributions of high-risk tissue (Figure 3), we observed no appreciable anterior shift in the distribution of high-risk tissue when the effective elastic modulus of the disc was varied within its physiological range (8–50 MPa), the high-risk tissue residing in the central trabecular bone and endplates. For higher disc stiffnesses, there was a severe anterior shift in the location of high-risk tissue.

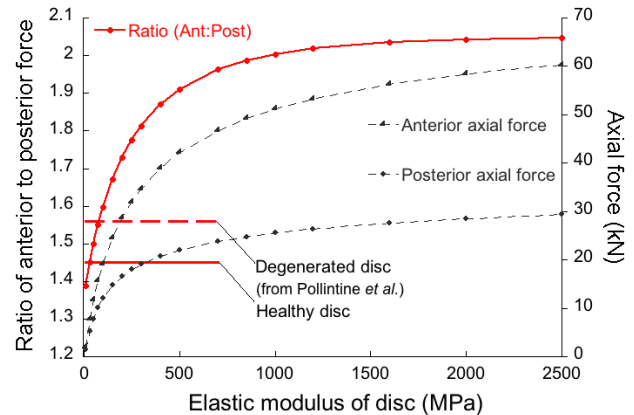


Figure 2. Axial force on the anterior and posterior halves of the superior endplate (and their ratio) vs. the effective elastic modulus of the disc.

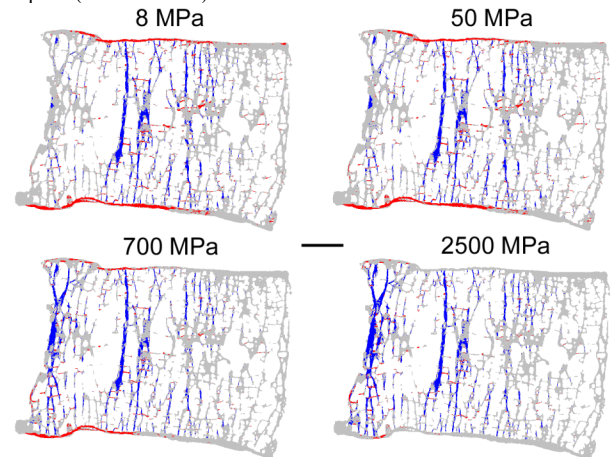


Figure 3. Mid-sagittal sections from the vertebra forward loaded via a disc layer having a modulus from 8–2500 MPa, showing the high-risk tissue, failing by compression (blue) or tension (red). Scale bar: 5 mm.

Discussion and Conclusion

Supporting validity of these results, in another cadaver study, Pollintine *et al.* [2] reported a ratio of anterior-to-posterior force acting on the disc of 1.4, which corresponds to an effective elastic modulus of the disc of 30 MPa from Figure 2; this value was also in the middle of our range of experimentally observed data in Figure 1. Further, with disc degeneration, Pollintine *et al.* [2] found that the anterior-posterior force ratio increased to 1.6, which corresponds from Figure 2 to a disc stiffness of 75 MPa, again, highly feasible based on our own experimental measurements (Figure 1). Our findings are further supported by a cadaver study which showed that, regardless of disc degeneration, the failure regions are in central endplate and underlying trabecular bone [4]. While forward bending tests via a stiff layer of PMMA produce very high stress in the anterior cortex, these collective results suggest that such a dramatic anterior shift in stress does not occur *in vivo* and thus does not explain the mechanisms of wedge fractures.

References

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