

Influence of structural and material properties on the risk of bony endplate failure during vertebral fracture

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INTRODUCTION: The endplate region of the human spine, consisting of the cartilage endplate, bony endplate (BEP), and subchondral bone (SB), forms the junction between the intervertebral disc and vertebral body. This region is frequently the site of vertebral fracture (VF), the most common type of osteoporotic fracture. Laboratory and clinical evidence indicates that the mechanisms of endplate failure during VF can vary. For example, only some VFs involve fracture of the BEP, while others appear to involve large, inelastic deformations in the SB without BEP fracture [1,2]. VFs that do involve fracture of the BEP are associated with higher risk of future disc degeneration and worsening of the fracture over time [3-5]. Identifying the factors that increase the risk of BEP failure can inform strategies for preventing and managing VFs. The goal of this study was to examine the influence of variations in the structural and mechanical properties of the BEP and SB on the risk of BEP failure during VF.

METHODS: Microcomputed tomography (μ CT) images of 14 L1 vertebrae (7M/7F; 41-91 yrs) were coarsened to generate baseline micro-finite element (μ FE) models (74 μ m elements). Material assignment prescribed a baseline tissue modulus ($E_t = 13$ GPa), Poisson's ratio ($\nu = 0.3$), and tissue plasticity according to an asymmetric bilinear model (yield strain: 0.41% tension, 0.83% compression; post-yield modulus reduced by 95% [6]). To allow modifications to the BEP and SB portions of the models, volumes of interest (VOIs) were identified corresponding to the BEP, SB, and the mid-vertebral body (MVB) (Fig 1) [7]. Four pairs of parametric variations were made to each baseline model: 1) thinning and thickening of the BEP by 22%; 2) lowering and raising SB volume fraction (BV/TV) by 12-22%; 3) lowering BEP tissue modulus while raising SB tissue modulus by 11% ("small") or 22% ("large"); 4) lowering and raising BEP tissue yield strain by 26%. These variation magnitudes corresponded to ~50% of the variance observed, or estimated to occur, in samples of BEP and SB specimens from human lumbar vertebrae [8]. Boundary conditions were assigned to the superior and inferior boundaries of each model. These boundary conditions were obtained from a prior study on these vertebrae [2] and corresponded to displacements measured via digital volume correlation at the vertebra's yield point during axial compression tests. Yield force was computed as the total axial reaction force at the superior boundary.

For each VOI, *yield fraction* was computed as the ratio of the number of yielded elements in the VOI to the total number of elements in the VOI. This fraction was then divided by the *total yield fraction*, defined as the ratio of the number of yielded elements in the entire model to the total number of elements in the model, to obtain the *normalized yield fraction* for that VOI. The normalized yield fraction expresses the yield in each VOI normalized to that of the full model; a value above one means that the VOI has a proportionally greater amount of yield than the vertebra as a whole. For each VOI and each of the four model variations, normalized yield fraction was compared among the levels of variation via repeated measures ANOVA. Strains at the BEP surface were omitted from the statistical analyses, to avoid boundary effects.

RESULTS: Normalized yield fraction in the BEP was greater than one for 11 of the 14 baseline models—indicating a high risk of yield in the BEP relative to the SB and MVB—and remained so irrespective of changes to BEP thickness (Fig 2). Lowering and raising SB BV/TV increased and decreased, respectively, normalized yield fraction in the SB ($p < 0.001$), and had the opposite effect in the MVB ($p < 0.001$) while leaving the BEP unaffected ($p > 0.05$). Lowering and raising BEP and SB tissue modulus, respectively, by small and then large amounts progressively increased the normalized yield fraction in the BEP while lowering it in the SB and MVB (all $p < 0.01$). Changing BEP yield strain had pronounced effects in all three VOIs ($p < 0.001$): in 12 of the 14 models, lowering the yield strain raised the normalized yield fraction in the BEP to above three and lowered that in the SB and MVB to less than one, whereas raising the yield strain lowered normalized yield fraction in the BEP to below one and raised that in the SB to greater than one. Yield force was unaffected by changes to BEP thickness ($p > 0.05$), but was reduced by a median of 14% when SB BV/TV decreased ($p < 0.01$) and increased by 10% and 20% when the moduli were changed by small and large amounts, respectively ($p < 0.01$).

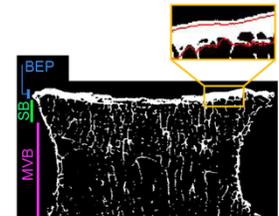


Figure 1. Definition of VOIs on a coronal slice; Inset: illustration of thickened BEP relative to the baseline model

DISCUSSION: Our results from systematic variation of BEP and SB properties demonstrate that the microstructure and material properties of these regions can critically affect the mechanisms of VF. Although the BEP remained the VOI at highest risk of yield for most of the model variations, changes in SB BV/TV and BEP tissue yield strain substantially modulated risk in the SB and MVB while having comparatively moderate effects on yield force. Given that the magnitudes of the model variations imposed in this study are commensurate with the amounts of variation estimated to occur in the population of human lumbar spines, these results suggest that differences in SB microstructure and BEP ductility may each help explain why some VF do not involve BEP failure. Of all model variations examined, changes to BEP tissue yield strain were most influential to relative risk of yield in the BEP, SB, and MVB, motivating further study of the factors that control BEP elasticity and ductility.

SCIENTIFIC/CLINICAL RELEVANCE: Despite the high prevalence of vertebral fractures, their pathogenesis is incompletely understood. The findings of this study suggest that population-level variations in the properties of the tissues in the vertebral endplate region can modulate which part of the vertebra is at highest risk for failure, which has implications for fracture prevention and management.

REFERENCES: [1] Holmes et al., *Spine* 1993; [2] Hussein et al., *J Biomech Eng* 2018; [3] Dudli et al., *Spine* 2014; [4] Holm et al., *J Spinal Disorders & Tech* 2004; [5] Wang et al., *Bone* 2013; [6] Bayraktar et al., *J Biomech* 2004; [7] Frings & Morgan, *JMBBM* 2025; [8] Thomsen et al., *Bone* 2002

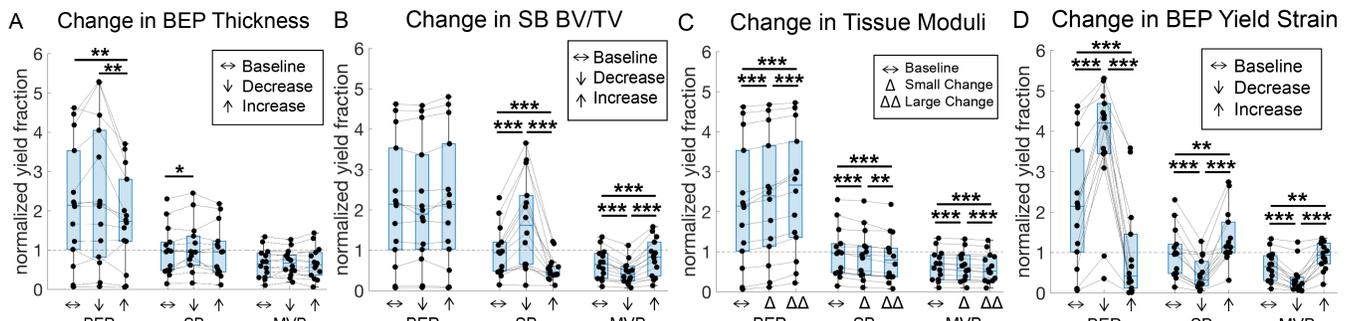


Figure 2. Effects of each of the four model variations (changes in: (A) BEP thickness; (B) SB BV/TV; (C) BEP and SB tissue moduli; (D) BEP tissue yield strain) on normalized yield fraction in each VOI. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.