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Effective modulus of the human intervertebral disc and its effect on vertebral bone stress

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ABSTRACT

The mechanism of vertebral wedge fractures remains unclear and may relate to typical variations in the mechanical behavior of the intervertebral disc. To gain insight, we tested 16 individual whole discs (between levels T8 and L5) from nine cadavers (mean ± SD: 66 ± 16 years), loaded in compression at different rates (0.05–20.0% strain/s), to measure a homogenized "effective" linear elastic modulus of the entire disc. The measured effective modulus, and average disc height, were then input and varied parametrically in micro-CT-based finite element models (60-μm element size, up to 80 million elements each) of six T9 human vertebrae that were virtually loaded to 3° of moderate forward-flexion via a homogenized disc. Across all specimens and loading rates, the measured effective modulus of the disc ranged from 5.8 to 42.7 MPa and was significantly higher for higher rates of loading ($p < 0.002$); average disc height ranged from 2.9 to 9.3 mm. The parametric finite element analysis indicated that, as disc modulus increased and disc height decreased across these ranges, the vertebral bone stresses increased but their spatial distribution was largely unchanged: most of the highest stresses occurred in the central trabecular bone and endplates, and not anteriorly. Taken together with the literature, our findings suggest that the effective modulus of the human intervertebral disc should rarely exceed 100 MPa and that typical variations in disc effective modulus (and less so, height) minimally influence the spatial distribution but can appreciably influence the magnitude of stress within the vertebral body.

1. Introduction

While anterior wedge fractures are the most common type of osteoporotic spine fracture, their etiology remains unclear (Adams and Dolan, 2012, 2011; Christiansen and Bouxsein, 2010). Presumably, an anterior wedge fracture – as opposed to a concavity fracture – occurs because the stress in the bone hard tissue is greatest in the anterior portion of the vertebral body. While cadaver experiments that apply forward-flexion loading to a vertebral body via a stiff layer of plastic do indeed produce anterior wedge-shaped fractures (Buckley et al., 2009; Dall'Ara et al., 2010; Rotter et al., 2015), experiments that load the vertebra through the disc typically produce bone failure in the trabecular bone and endplates more centrally, that is, not anteriorly (Farooq et al., 2005; Granhed et al., 1989; Hutton and Adams, 1982; Jiang et al., 2010; Landham et al., 2015). Consistent with these findings, micro-CT-based finite element analyses (Fields et al., 2010; Yang et al., 2012) have shown that, for both compression and forward-flexion loading applied via a simulated compliant homogenized disc (Young's modulus of 8 MPa), the highest stresses in the vertebral bone occur mostly centrally in the trabecular bone and endplates, whereas high stress occurs anteriorly only when the flexion loading is applied via a stiff layer of plastic (Young's modulus of 2500 MPa).

As far as the etiology of the anterior wedge fracture is concerned, the question then arises as to what is the influence of typical variations in the disc properties on the vertebral bone stresses – can typical variations in disc properties increase the risk of an anterior wedge fracture? While the material properties and morphometry of the disc can appreciably change with aging and degeneration (Adams and Roughley, 2006; Alkalay, 2002; Inoue and Espinoza Orias, 2011; Natarajan et al., 2004), and while disc degeneration and loss of height are associated with an increased *in vivo* risk of vertebral fractures (Castano-Betancourt et al., 2013; Sornay-Rendu et al., 2006, 2004), it is still unclear if and how *typical variations* in the overall mechanical properties of a disc can influence either the location of highly stressed bone tissue within the vertebra or the overall magnitude of stress. Addressing this issue, we performed cadaver experiments to measure typical

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variations in a homogenized "effective" elastic modulus of the entire disc, and then varied those properties parametrically in a micro-CT-based finite element analysis of multiple vertebral bodies to determine the role of the observed typical variation in the disc properties on tissue-level bone stress in the vertebral body.

2. Materials and methods

2.1. Mechanical testing of cadaveric intervertebral discs

Uniform compressive mechanical testing was performed on cadaver whole discs to measure a homogenized "effective" linear elastic modulus of the entire disc (henceforth termed the "effective modulus"). This type of measurement characterizes the average linearized behavior of the entire disc, treating it as a homogeneous elastic material. While this characterization clearly simplifies the more complex behavior of a real disc, it nonetheless provides a single metric for quantifying the mechanical behavior of the entire disc and facilitates numerical implementation of disc behavior into large-scale finite element models of whole vertebrae.

The whole-disc specimens, attached to their adjacent vertebral bodies, were prepared from 16 bone-disc-bone vertebral motion segments. These segments were disarticulated from nine anonymous donor spines aged 66 ± 16 years (mean $\pm$ SD), seven male and two female, with seven spines yielding two motion segments each and the remaining two spines yielding one motion segment each. All motion segments were between levels T8 and L5, and segments from the same spine were either neighboring or one level apart.

For each whole-disc specimen, the vertebral body portions were reinforced so that the recorded deformations of the loaded test specimens would reflect primarily the deformations of only the disc. To reinforce the specimens, the posterior elements were removed and the respective top/bottom parts ($\sim$5–10 mm in height) of each vertebral body were sectioned off in a transverse plane, resulting in a sectioned-vertebra/disc/sectioned-vertebra test specimen (Fig. 1A). A Dremel tool was then used to hollow out each vertebral body to within approximately 5 mm from both the endplate and the cortical shell, a water jet was used to remove any marrow, and a syringe was used to maximally fill each vertebral body with polymethylmethacrylate (PMMA). Each reinforced specimen was stored overnight at 4 °C and then embedded at each end in parallel 2 mm-deep PMMA wells to provide parallel flat PMMA-surfaces for loading (Fig. 1A). Before mechanical testing, an average disc height was measured from anterior–posterior and medial–lateral radiographs. Disc degeneration was evaluated according to a five-category grading system proposed by Thompson et al. (1990).

Uniform compression testing was performed to measure the effective modulus for different strain rates. To reduce disc hydration, we applied an initial compressive load of 300 N and allowed the specimen to stress-relax for 15 min (McMillan et al., 1996), at which point we set the deformation reading to zero. Each specimen then underwent five dynamic preload cycles to 10% strain at a strain rate of 0.5%/s and was then compressed to failure (50% strain) at either a "low" (0.05%/s) or "high" (20%/s) strain rate. In all tests, stress was defined as the recorded force divided by the cross-sectional area of the disc and strain as the recorded platen-to-platen deformation divided by the average disc height. From the resulting stress-strain curve, we defined the effective modulus as the linearized secant modulus from the point of zero deformation to the point of maximum stress (Fig. 1B).

2.2. Parametric finite element analysis

Finite element models for six T9 vertebral bodies were adapted from those used in prior studies (Eswaran et al., 2006, 2007; Fields et al., 2010; Yang et al., 2012). In brief, six fresh-frozen T9 human whole vertebral bodies were obtained from cadavers ($n=5$ male; $n=1$ female; age range: 53–91 years, mean $\pm$ SD $=75 \pm 15$ years) with no medical history of metabolic bone disorders and then scanned with micro-CT using a 30-μm voxel size (Scanco 80; Scanco Medical AG, Brüttisellen, Switzerland). The micro-CT scans were coarsened to isotropic 60-μm voxels, segmented using a global threshold value, and the bone tissue was compartmentalized into trabecular bone, endplate and cortical shell regions. By directly converting each coarsened voxel into a finite element (Van Rietbergen et al., 1995), finite element models of each vertebral body were created, each model having up to $\sim$80 million elements and over 300 million degrees of freedom. In these models, each bone element was assigned the same linearly elastic material properties (elastic modulus of 18.5 GPa and Poisson's ratio of 0.3) and the disc was modeled as a homogeneous, isotropic, linearly elastic material that covered each endplate. Since the endplates have variable geometry, the height of the simulated disc was defined as twice the distance from the most superior or inferior end of the vertebra to an assumed line of mid-symmetry of the disc (Fig. 1C). Boundary conditions were applied to simulate 3° of moderate forward-flexion by rotating the top surface of the superior half-disc in a mid-sagittal plane about the most superior-posterior

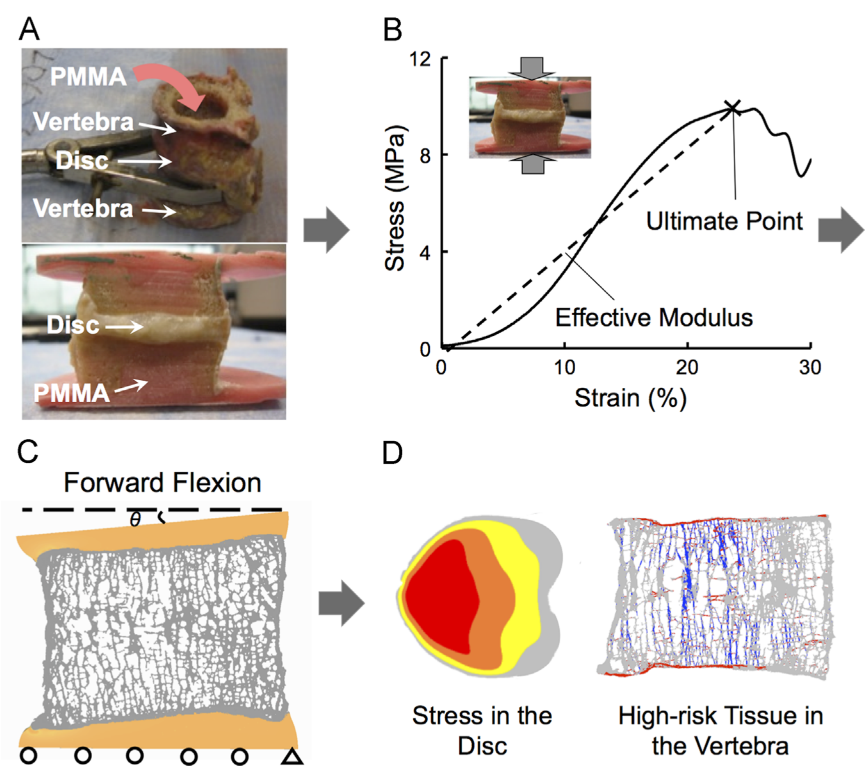

Fig. 1. Overall study design: (A) The center of the vertebra of the bone-disc-bone motion segment was hollowed out and infilled with polymethylmethacrylate (PMMA) in order to limit any deformation of the vertebral endplates; (B) mechanical testing was performed on the bone-disc-bone preparations to measure an effective modulus of the entire disc; (C) these measurements, and those of average disc height, were used as input to a parametric finite element analysis simulating a moderate degree of forward-flexion loading ($\theta=3°$) applied to a different cohort of vertebral specimens; (D) the main outcomes were the stress in the disc (red indicates the region being the highest loaded, gray the least) and the distribution of high-risk tissue within the vertebral body (red and blue indicate the presence of high-risk tissue in tension and compression, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)