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Accuracy of finite element analyses of CT scans in predictions of vertebral failure patterns under axial compression and anterior flexion

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ABSTRACT

Finite element (FE) models built from quantitative computed tomography (QCT) scans can provide patient-specific estimates of bone strength and fracture risk in the spine. While prior studies demonstrate accurate QCT-based FE predictions of vertebral stiffness and strength, the accuracy of the predicted failure patterns, i.e., the locations where failure occurs within the vertebra and the way in which the vertebra deforms as failure progresses, is less clear. This study used digital volume correlation (DVC) analyses of time-lapse micro-computed tomography (μCT) images acquired during mechanical testing (compression and anterior flexion) of thoracic spine segments (T7–T9, $n=28$) to measure displacements occurring throughout the T8 vertebral body at the ultimate point. These displacements were compared to those simulated by QCT-based FE analyses of T8. We hypothesized that the FE predictions would be more accurate when the boundary conditions are based on measurements of pressure distributions within intervertebral discs of similar level of disc degeneration vs. boundary conditions representing rigid platens. The FE simulations captured some of the general, qualitative features of the failure patterns; however, displacement errors ranged 12–279%. Contrary to our hypothesis, no differences in displacement errors were found when using boundary conditions representing measurements of disc pressure vs. rigid platens. The smallest displacement errors were obtained using boundary conditions that were measured directly by DVC at the T8 endplates. These findings indicate that further work is needed to develop methods of identifying physiological loading conditions for the vertebral body, for the purpose of achieving robust, patient-specific FE analyses of failure mechanisms.

1. Introduction

Vertebral fractures are the most common type of osteoporotic fracture (Burge et al., 2007) and are associated with increased morbidity and excess mortality. Prevalent vertebral fracture increases the risk of subsequent vertebral and hip fracture two- to three-fold (Black et al., 1999; Cauley et al., 2007; Klotzbuecher et al., 2000), and there is a 20% increased risk of death five years following clinical vertebral fracture (Cooper et al., 1993). Current methods of estimating fracture risk in the spine are based on measurements of bone mineral density (BMD) by dual-energy x-ray absorptiometry (DXA). However, BMD explains only approximately 60% of the variation in vertebral strength (Cheng et al., 1997), and almost half of patients with vertebral fracture do not exhibit osteoporotic values of BMD (Kanis et al., 2002). Finite element analysis (FEA) of quantitative computed tomography (QCT) scans of the vertebra has long been proposed as an improved method (Faulkner et al., 1993; Keaveny, 2010; Zysset et al., 2013). Given the use of QCT-based FEA for evaluating osteoporosis therapies and other drug treatments (Gluer et al., 2013; Keaveny et al., 2007), sex-related differences in bone strength (Christiansen et al., 2011), and implant designs (Polikeit et al., 2003), the accuracy of this method must be fully established.

Prior studies have found that QCT-based FEA can provide good predictions of vertebral stiffness and strength, yet the evidence regarding predictions of failure patterns, i.e., the locations where failure occurs within the vertebra and the way in which the vertebra deforms as failure progresses, is less clear. Compressive stiffness and strength computed by QCT-based FEA are highly

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correlated with values measured in laboratory tests (Bozic et al., 1994; Buckley et al., 2007b; Crawford et al., 2003; Dall'Ara et al., 2012; Imai et al., 2006; Wang et al., 2012). QCT-based FE estimates of vertebral strength under compressive loading are also associated with fracture even after adjusting for BMD (Kopperdahl et al., 2014; Wang et al., 2012) and discriminate between fracture and non-fracture cohorts better than BMD (Imai et al., 2006). However, QCT-based FEA has not performed as well for anterior flexion (Buckley et al., 2007a; Dall'Ara et al., 2010). Studies also suggest that FEA predictions of vertebral failure patterns can be inaccurate because of the highly non-uniform loading applied across the vertebral endplates by the adjacent intervertebral discs (IVDs) (Adams and Roughley, 2006; Clouthier et al., 2015; Hussein et al., 2013b; Jones and Wilcox, 2008; Maquer et al., 2015; Maquer et al., 2014). Moreover, the impact of the choice of material properties for bone tissue, and in particular the yield criterion, on the accuracy of the FEA predictions of failure patterns has not been addressed.

The goal of this study was to assess the accuracy of QCT-based FEA in predicting vertebral failure patterns. QCT-based FEA calculations of displacements throughout the vertebral body were compared to those measured via digital volume correlation (DVC) analyses of micro-computed tomography (μCT) images acquired as the vertebrae were loaded to the ultimate point. The specific objectives were to evaluate the accuracy of the FEA-computed displacements: (1) for different boundary conditions, representing either rigid platens or IVDs; (2) in two different loading modes (axial compression, axial compression combined with anterior flexion); and (3) for different yield criteria. We hypothesized that boundary conditions based on specimen-specific data on IVD degeneration would improve the FEA predictions, for both loading modes and both yield criteria.

2. Materials and methods

2.1. Specimen Preparation

Twenty-eight T7–T9 spine segments were dissected from fresh-frozen human spines (age: 35–91 years; mean ± stdev: 71.2 ± 14.2 years; 16 male, 12 female) and were potted in polymethyl methacrylate (PMMA) (Fig. 1A). Specimens were kept

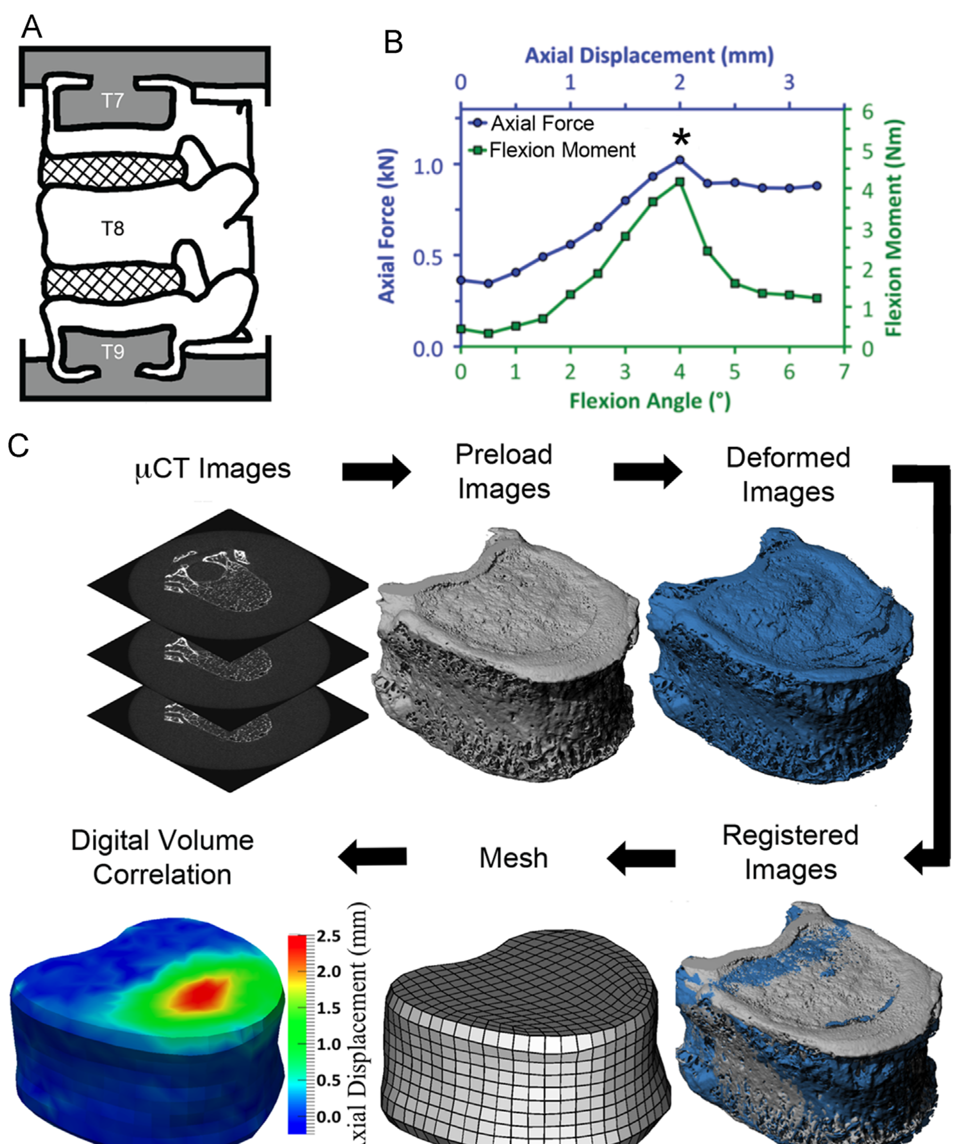

Fig. 1. (A) Preparation of the T7–T9 spine segments (grey = PMMA; cross-hatch = IVD; white = bone); (B) Mechanical testing involved stepwise loading with a μCT scan performed at each loading step; the asterisk denotes the peak of loading, which was the loading step used for comparison of the measured and FE-computed displacements; (C) Experimental procedure for image processing in preparation for digital volume correlation; The output of the digital volume correlation are the displacements occurring throughout the T8 vertebral body, though only the axial displacements on the surface of T8 are depicted in the figure.