Stress analysis of osteoporotic lumbar vertebra using finite element model with micro-scaled beam-shell trabecular-cortical structure

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Abstract. Osteoporosis is a disease in which low bone mass and micro-architectural deterioration of bone tissue lead to enhanced bone fragility and susceptibility to fracture. Due to the complexity and difficulty of in vitro experiments, finite element models have been developed to analysis the biomechanical properties of the vertebral body. We developed models of L2 vertebra, which consisted of endplates, trabecular lattice, and cortical shell, for three age-related grades (young, middle, and old). The compressive strength and stiffness results revealed that we had developed a valid model that was consistent with the results of previous experimental and computational studies. Von-Mises stress, which was assumed to predict the risk of burst fracture, was also determined for three age groups. The results showed that the von-Mises stress was substantially higher under relatively high levels of compressive loading, which suggested that patients with osteoporosis should be cautious of fracture risk even during daily activities.

Keywords: Osteoporosis, Beam-shell structure, Spine, Finite element modeling, Biomechanics

1 Introduction

Osteoporosis is a disease in which low bone mass and micro-architectural deterioration of bone tissue lead to enhanced bone fragility and susceptibility to fracture. Osteoporosis is one of the most common health problems affecting both men and women, and it is becoming increasingly prevalent in our aging society. About 1.5 million fractures due to osteoporosis are reported annually in the United States, including over 700,000 vertebral fractures [1]. Spine fractures in particular result in a high mortality rate: survival is 72% in the first year and only 28% after five years [2]. So it is so urgent to investigate the mechanism of the vertebral fractures. Due to the complex anatomy of the vertebral body, the difficulties associated with obtaining bones for in vitro experiments and the limitations on the control of the experimental parameters, finite element models of normal and various grades of osteoporotic
lumbar vertebrae that incorporate the micro-scaled trabecular structure of lattice models and the cortical area of shell elements were developed. The models were validated using the results of previous experimental and computational studies. The von-Mises stress was analyzed to predict the risk of the burst fracture in osteoporotic bones of various grades.

2 Materials and Methods

We developed a cylindrical core lattice model composed of vertical and horizontal struts for different age groups: young (<50 years), middle (50 – 75 years), and old (>75 years). The horizontal and vertical thicknesses, and length of each strut, are provided for each age group based on [3, 4]. In order to mimic the irregular structure of the trabecular struts, the lattice models were perturbed by randomly moving vertex nodes with MATLAB [3, 5]. The distance that each vertex node was moved ranged between 0% and 30% of trabecular spacing (horizontal and vertical lengths) according to a Gaussian distribution [4]. The direction was also randomly generated to prevent the model from having a bias in one direction. Based on L2 CT images, two endplates and the cortical part of the vertebra were developed. The trabecular lattice was tied with the cortical shell and endplates (Figure 1). In this case, the posterior element of the vertebra was not considered because the whole vertebral body has too many elements, and the posterior element plays only a minor role during compressive loading. The compressive strength and stiffness were calculated and compared with those from previous experimental and computational studies for validation of the model. The von-Mises stress in the trabecular lattice was then analyzed for the three age groups (young, middle, and old) under compressive loading. The compressive loading on the entire upper endplate was assumed to be 0.15MPa, 0.3MPa, 0.45MPa, 0.6MPa and 0.75MPa, because the pressure on the endplate was considered to be 0.3MPa in upright standing [10, 11]. The ABAQUS/Explicit (Dassault Systèmes, RI, USA) was used for the analysis.

3 Results

The compressive strength of the trabecular bone lattice model was 1.74MPa for the middle, while it was 1.35±0.64MPa in [5]. For the whole body model, the compressive strength was 7.35MPa for the young group, 3.80MPa for the middle group, and 1.38MPa for the old group. In a previous computational study with the same age classes, the compressive strength was 5.74MPa for the young group, 4.06MPa for the middle group, and 1.25MPa for the old group [3]. In experimental studies using normal vertebrae, the compressive strengths have ranged from 0.9 to 15.9MPa [6-9]. In addition, the compressive stiffness was 5.6kN/mm for the young group, 15.8kN/mm for the middle group, 29.4kN/mm for the group. In a previous computational study, compressive stiffness was 8.0kN/mm for the young group, 18.7kN/mm for the middle group, and 29.4kN/mm for the old group [3]. These results
indicate that the presented model could be considered as being validated for the compression.
The highest von-Mises stresses occurred in the middle of the trabecular region. The maximum stress was strongly related to age: maximum values were about 50% higher for the middle group than the young group and about 120% higher for the old group than the young age group (Figure 2). In addition, the maximum stress was greater than 50% of the yield stress (64MPa) when compressive loading exceeded 0.45MPa for middle group and 0.3MPa for the old group; in contrast, the maximum stress did not reach 50% of the yield stress even under 0.75MPa for the young group.

Fig. 1. Lattice models with a trabecular structure after perturbation for three age groups: young (< 50 years); middle (50 – 75 years); and old (> 75 years); and the whole vertebral model including trabecular lattice, cortical shell and endplates (middle represent)

Fig. 2. (a)Maximum stress for the three age groups; (b) Ratios of the maximum stress for the middle and old groups relative to the young group: under 0.15MPa, 0.3MPa, 0.45MPa, 0.6MPa and 0.75MPa of compressive loading
4 Discussion

Osteoporosis is a major contributor for the increased risk of fracture with age due to low bone mass and structural change. In order to mimic a realistic trabecular structure, we developed a model in which perturbation of the vertex nodes occurred within 30% of the trabecular spacing according to a Gaussian distribution. The 0.45MPa of compressive loading on the endplate equates to about 0.7MPa of intradiscal pressure, which is similar to that produced during daily activities, such as standing while bent forward (1.10MPa), standing up from a chair (1.10MPa), and lifting or holding a weight of 20 kg (1.10–2.30MPa). The von-Mises stress, which was assumed to predict the risk of a burst fracture, was determined for the three age groups. The results suggest that osteoporosis can affect the stress acting on the vertebra even during routine daily activities.

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References