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The Behavior of Thoracic Trabecular Bone during Flexion

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Thoracic compression fractures are often described as anterior wedge fractures. Although the radiographic signs of these fractures are easily identified, the mechanism of the trabecular failure is not well understood. The current study addressed this mechanism in the lower thoracic spine by measuring the trabecular strain. Trabecular strain was measured in six human thoracic cadaver spines during 1) compressive and 2) flexural loading. The strains were measured at incremental loads using a texture correlation. They were analyzed by global contour plots and regional analysis of the T11 vertebrae. Specimens loaded under only compression exhibited uniform strains in the vertebral body. During flexion, however, the strains were concentrated in the anterosuperior margin of the vertebral body and the compressive and shear strain magnitudes in this region were significantly increased. These results demonstrate that the flexural position places the lower thoracic spine at greater risk of anterior compression fracture as seen clinically.

Key words: trabecular strain, compression fracture, thoracic spine, flexion, biomechanics

INTRODUCTION

Vertebral compression fractures commonly occur in the elderly. More than 700,000 compression fractures occur in the United States annually, and the prevalence increases with age [16, 19]. In women over the age of 70 years, the prevalence of vertebral fractures is between 15% and 35%, and in women over the age of 80 years, the prevalence is between 25% and 50% [8, 22]. Vertebral compression fractures most commonly occur in the thoracolumbar region (T11-L1) [17, 22].

Two-thirds of patients with a single compression fracture are asymptomatic, but with increasing number and severity of fractures, patients become more symptomatic and disabled [4, 6]. Since the pain is often persistent, many patients with such fractures suffer for long periods of time.

Studying the strain behavior and failure mechanisms of the thoracic spine is important in understanding the etiology of such fractures. The shape of the compression fracture in the lower thoracic spine is often seen as an anterior wedge fracture on lateral radiographs. It is said that the curvature and load distribution of the thoracic spine may be related [18, 25]. However, the behavior of the compression fracture is not well understood.

Two hypotheses have been identified to explain these fractures. First, material property changes that occur during aging could weaken the trabecular bone in specific regions of the vertebral body. Second, postural changes such as increased kyphosis could change the loading conditions on the vertebral body. The specific aims of the current study were to quantify and compare the thoracic trabecular strain during compression and compression-flexion.

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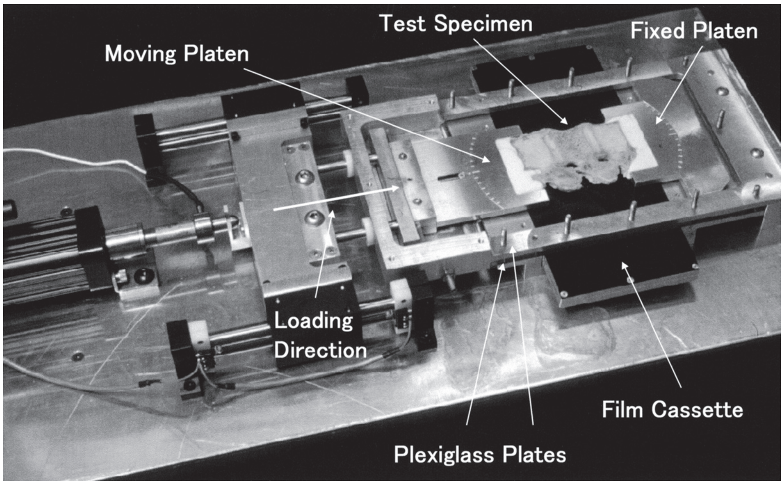

Fig. 1 The custom loading frame
The specimen is fixed between upper and lower plexiglass plates to avoid out of the loading plane. Radiographic film is exposed within a sliding cassette positioned under the lower plexiglass plate.

MATERIALS AND METHODS

Specimen Preparation

Six human cadaver lower thoracic spines (T10-T12) were procured and cleaned of muscle and adipose tissue. Each specimen was radiographically screened to exclude metastatic or metabolic diseases and osteophytes. The average age was 73.5 years and ranged from 52 to 91 years. The mean bone mineral density (BMD) of the thoracic specimens was 0.703 g/cm^2 and ranged from 0.424 to 1.049 g/cm^2. The specimens were sectioned to 10-mm thick samples along the right or left pedicular planes by a band saw. Next, they were precisely ground to 6.35 ± 0.05 mm thick sections using a custom cryo-vise and conical grinding wheel mounted to a standard milling machine. The trabecular bone areas of the superior (T10) and inferior (T12) vertebral bodies were secured and embedded in polymethylmethacrylate (PMMA; Coe Laboratories, Chicago, IL), and molded between the exposed superior endplate of T10 and inferior endplate of T12 and the respective loading platens in PMMA. Every spine was wrapped in saline-soaked gauze and sealed in plastic bag. They were kept at −20°C until testing.

Experimental Test Method

Before testing, the specimens were thawed to room temperature. They were mounted in a custom-loading frame housed in a contact radiography unit (Figs. 1 and 2) that allowed for loading and high resolution radiographic imaging of the specimens [1, 2, 24, 26]. For the compressive loading scenario, the specimens were placed in the neutral, slightly kyphotic position with the endplates of each vertebral body relatively parallel to one another (Fig. 3). The compressive load was applied by using a linear stepper motor and loads were applied every 50 N from 0 N to 150 N from cephalic side of the specimens. These loads were based on the estimated stress experienced by the lower thoracic endplates during standing. Specimens were also loaded using a compressive-flexural bending load. The load was created by applying a 20 mm anterior offset for the stepper motor. This resulted in applied bending moments from 0 to 3 Nm in increments of 1 N as well as the superimposed compressive load from 0 to 150 N in 50 N increments. The order of testing was altered between compression and compression- flexion among the specimens. During each load increment, radiographs were taken of the vertebral sections under unloaded and loaded conditions. Before each radiograph the specimens were allowed to relax for 45 seconds. Then each radiograph was exposed using 50 kVp for 70 seconds with Industrex M film (Eastman Kodak Company; Rochester, NY).

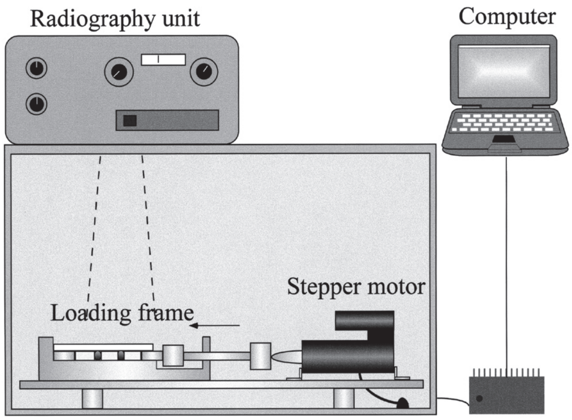

Fig. 2 Custom loading frame housed in a contact radiography unit

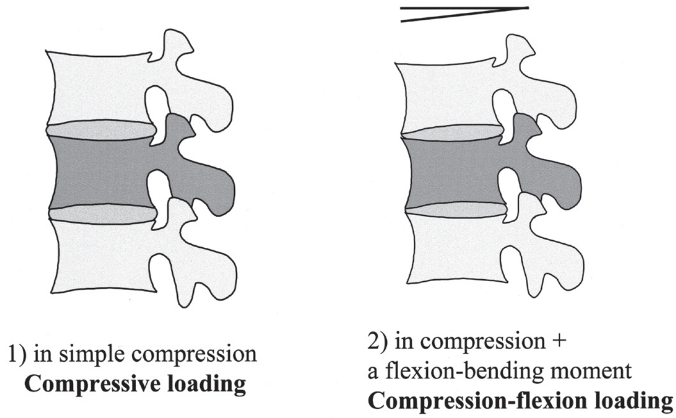

Fig. 3 Two conditions
The testing order was alternated between treatments 1) and 2) to avoid a bias in the results due to testing order. The flexural bending moment was applied using a 20-mm off-set loading platen.

Data Analysis

The radiographs were digitized using a 16 bit digital camera (Photometrics; Tucson, AZ) with a 1024×1024 resolution. The trabecular area of interest (T11) was divided into 51×41 nodes using Patran (Patran V 5.0; The MacNeal-Schwendler Corp., Los Angels, CA). Using texture correlation [1], compressive and shear strains within the T11 vertebral body of each specimen were measured at each node during compression and compression-flexion states for each load increment. The spatial distribution of the trabecular strains was described using a contour plot (Delta Graph; Delta Point, Monterey, CA). In addition, the T11 vertebral body was divided into four regions as follows: anterosuperior, posterosuperior, anteroinferior, and posteroinferior.

The population of strains within the spatially averaged distribution was characterized by measures of central tendency and dispersion. During preliminary testing it was apparent that the strain population within the vertebral body was not normally distributed [2]. Therefore, the strain distribution was transformed using a Log-Normal Transformation (Stata Statistical Software; Stata Corp., College Station, TX) and three values were calculated: the mean, the mean minus 1 standard deviation, and the mean plus 1 standard deviation. These values

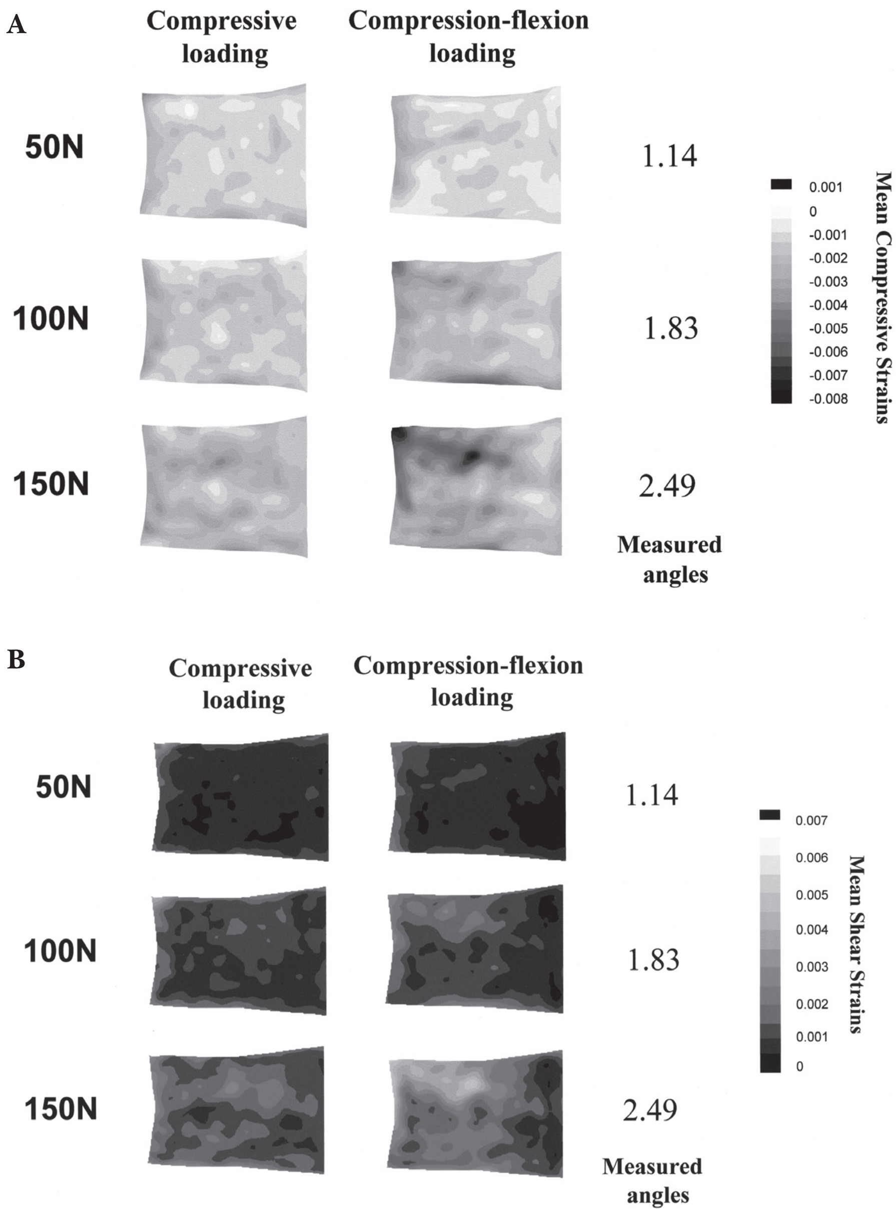

Fig. 4 Contour plots of the two conditions. (A) Minimum compressive strains and (B) maximum shear strains. Each is scaled to the same range shown in the right.

were then restored to units of strain through the inverse transform. The mean strains were compared between the two loading conditions in each region using a single factor analysis of variance with a level of significance of 0.05.

RESULTS

The mean measured angles (the T10 to T12) during compression-flexion loading were as follows: 1.14±0.8° at 1 Nm and 50 N, 1.83 ±1.16° at 2 Nm and 100 N, and 2.49+1.57° at 3 Nm and 150 N.

Spatial Strain Distribution

The peak compressive and shear strain magnitudes during the compression-flexion loading were greater than those during compression loading (Figs. 4A and 4B). The compressive and shear strains during compressive loading were distributed

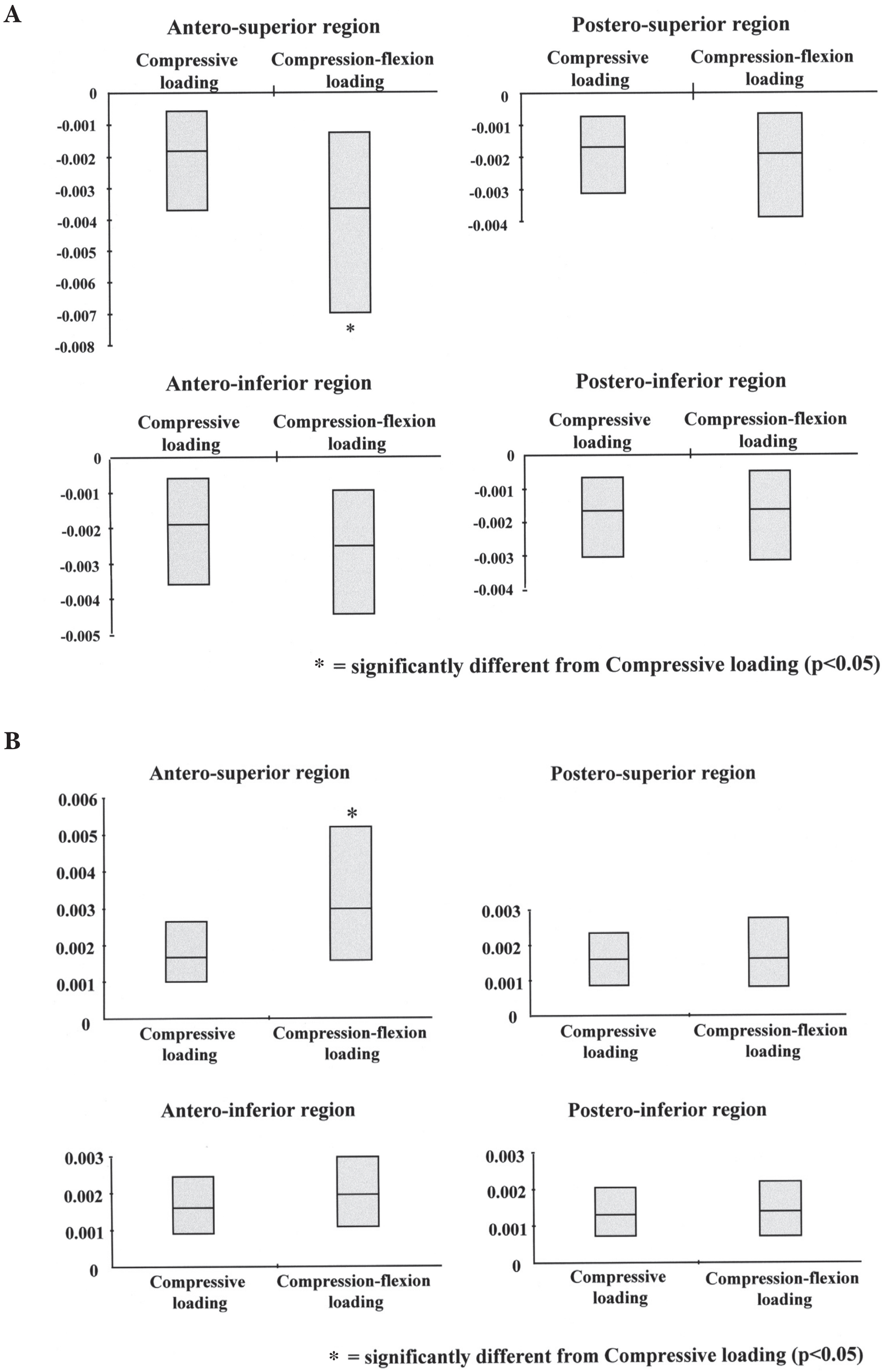

Fig. 5 (A) Minimum compressive strains and (B) maximum shear strains of the two conditions at 150N. Bars illustrate the average low, mid, and high range values for the 6 samples.

relatively uniform, while the same strains during compression-flexion loading were concentrated toward the anterosuperior region of the vertebral body and increased with incremental loading.

Regional Strains

The mean compressive strain magnitude in the anterosuperior region of the specimens during compression-flexion loading was significantly greater than that of the specimens loaded in compression (Fig. 5A). Similar findings were observed for the maximum shear strain (Fig. 5B). In the anterosuperior region, the maximum shear strain during compressive-flexion loading was significantly greater than the maximum shear strain during compressive loading. No significant differences between loading conditions were observed in the other three regions.

DISCUSSION

Thoracic compression fractures are a common occurrence in the elderly kyphotic population – especially in the lower thoracic spine [18]. It is hypothesized that the increased stress present at the thoracolumbar junction is responsible for the majority of such fractures. However, the influence of the flexural position or tissue property dependency of thoracic fractures has not been characterized.

Faulkner *et al.* studied the effect of the distribution between trabecular and cortical bone on vertebral strength using finite element analysis [7]. Ito *et al.* investigated the relationships between trabecular and cortical bone mineral densities to vertebral fractures [12, 13]. They stated that the strength depended strongly on the cortical bone with deteriorated trabecular bone. Trabecular bone mineral density can be a good predictor of spinal fracture [13].

While several articles have focused on the tissue properties of the vertebrae, no studies have discussed the regional distribution of the trabecular bone within the thoracic vertebral body. In the current study, the trabecular bone within the sectioned T11 specimens was uniformly distributed on a gross scale and the corresponding strains during compressive loading were also uniformly distributed. Therefore, regional variations in the trabecular architecture may not be responsible for the consistent anterosuperior location of compression fractures seen clinically.

Anterior compression fractures are often seen clinically in the lower thoracic spine at or near the thoracolumbar junction. The thoracolumbar junction is the union of the stiff thoracic and compliant lumbar regions. Also, since it is the transition between the kyphotic thoracic region and lordotic lumbar region, it is relatively straight as demonstrated by Bernhardt and Bridwell [3]. The high stresses and strains generated in this region are believed to be responsible for the high occurrence of anterior wedge fractures at the thoracolumbar junction. Some investigators describe that such fractures may be related in the shape and load distribution of the lower thoracic spine [18, 25]. De Smet *et al.* reported that anterior wedge fractures were commonly seen about thoracolumbar junction [5]. Meyer noted that thoracic spine fractures most commonly resulted from flexion injuries that occurred during vehicular accident or falls [20].

From a biomechanics standpoint, some have investigated the biomechanics of these fractures for thoracic or lumbar vertebra. Hansson and Roos studied the relationship between the bone mineral content and the ultimate compressive strength [10]. They reported that the wedge type of fracture was consistent with lower bone mineral content and more severe disc degeneration. Ochia and Ching measured an intraosseous pressure within vertebrae increase under two displacement rates during under axial-compressive loading conditions [21]. The study suggested that the displacement rate was an important factor in creation of burst fractures and the slow-speed test resulted in only compression fracture. Kifune *et al.* investigated assessment fracture instability using three-dimentional flexibility [15]. The study showed that the wedge fracture was mechanically stable in only some parameters. A few researchers have investigated these fractures using surface strain measurements, and Kayanja *et al.* said that anterior cortical strain is concentrated at the apex of a thoracic kyphotic curve [11, 14].

However, the mechanism of anterior wedge fractures in the lower thoracic spine is not well understood. By investigating the behavior of vertebral trabecular strain under a combined compressive axial and flexural load, a better understanding of the lower thoracic compression fracture is possible.

Previous studies have reported trabecular strain values using finite element models [9, 23]. The current study incorporated an experimental technique that allows for extremely accurate and direct measurements of trabecular strain [24, 26]. The results of the current study demonstrate that high trabecular strains are concentrated the anterosuperior quarter of the lower thoracic vertebra during flexural bending, but strains are relatively evenly distributed during neutral compression load.

Since no local lesions or variations of the trabecular architecture were identified in any of the specimens used, the current data support the second hypothesis, that loading changes resulting from postural changes are primarily responsible for anterior wedge compression fractures. These results indicate that even mild degrees of forward flexion in the lower thoracic spine may lead to compression fractures as seen clinically. The results of the current study also place an important emphasis on anterior restoration or augmentation of the load-bearing structures of the anterior thoracic spine when performing such procedures as vertebroplasty or kyphoplasty.

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