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ORIGINAL ARTICLE

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# Damage-based finite-element vertebroplasty simulations

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**Abstract** The objectives of this study were to quantify the efficacy of vertebroplasty according to: (1) damage and (2) cement quantity (fill) and modulus. Vertebral body damage was numerically simulated using a previously validated two-dimensional finite-element model coupled with an elasto-plastic modulus reduction (EPMR) scheme. The effects of cement fill (% marrow replaced by cement, % MRC) and cement modulus on vertebral apparent modulus and trabecular bone tissue stress concentrations were parametrically assessed for four EPMR damage models (19%, 33%, 60%, and 91% modulus reduction). For this analysis, the elastic modulus of the trabecular bone tissue and marrow elements were assumed to be 10 GPa and 10 kPa, respectively. The effect of cement modulus (varied in the range 1 GPa to 9 GPa) on vertebral apparent modulus was also examined for partial fill (39% MRC) and complete fill (100% MRC) using the 33% modulus reduction damage model. In the case of polymethylmethacrylate (PMMA cement modulus = 2.16 GPa), restoration of the thoracic vertebral body (T10) apparent modulus to undamaged levels required 71% and 100% cement fill for the 19–33% and 60–91% modulus reduction damage models, respectively. Variations in cement modulus had no appreciable effect on the recovery of vertebral apparent modulus to undamaged levels for simulations of partial cement fill (39% MRC). For complete cement fill, however, a PMMA cement modulus produced approximately a 2-fold increase (82%) in vertebral apparent modulus relative to the undamaged vertebral body. Increasing the cement modulus to 9 GPa increased the vertebral apparent modulus over 2.5-fold (158%) relative to the undamaged state. The EPMR damage scheme and repair simulations performed in this study will help clinicians and cement manufacturers to improve vertebroplasty procedures.

**Key words** Bone cement · Vertebroplasty · Vertebral osteoporotic compression fracture · Trabecular bone · Finite-element analysis

## Introduction

Osteoporosis is a systemic disease characterized by skeletal fragility [12, 27]. Throughout the progression of this disease, atrophy of the trabecular density results in an increased rate of fracture. Osteoporotic vertebral fractures, estimated to be more than 500,000 in the United States each year [12, 23, 28], have been reported to occur even at relatively low loads such as encountered during routine daily activities [17, 18]. Vertebral fractures may lead to spinal deformity, chronic pain, reduced mobility, depression, sleep loss, and, in extreme cases, increased morbidity [7, 9, 10, 12, 18, 23]. Traditional management of os-

teoporotic vertebral fractures includes physical therapy, bed rest, drug therapies, bracing [23, 25, 26, 33], and, in recent years, vertebroplasty and kyphoplasty [9, 23].

Vertebroplasty involves the forced injection of bone cement, usually polymethylmethacrylate (PMMA), through one (unipedicular) or two (bipedicular) pedicles using bone biopsy needles into the closed space of a collapsed vertebral body [9, 23]. Cement can also be injected parapedicularly (transcostovertebral) for a more midline cement fill. Unlike traditional treatments requiring bed rest and immobilization, which may increase skeletal fragility, vertebroplasty provides immediate pain relief and stabilization [3, 9, 23].

Complications of vertebroplasty are primarily related to injection of cement and include cement leakage into paravertebral soft tissues, foraminal veins, and foraminal space with a symptomatic complication rate of less than 1% in patients with osteoporosis and 5–10% in patients with malignant tumors [8]. In addition, vertebroplasty has been reported to alter the load transfer in vertebral motion segments, and has been suggested to be the cause for a higher incidence of adjacent vertebral fractures observed clinically [1, 5].

Currently, cement deposition inside the vertebra during vertebroplasty can be partially controlled, but clinicians generally must empirically select the volume of cement needed to restore vertebral strength and stiffness [3]. Recent biomechanical investigations of vertebroplasty have examined the effects of cement composition [2, 3, 4, 25], cement volume [3, 24], and surgical approaches (unipedicular and bipedicular) [24, 33] on vertebral mechanical properties (typically stiffness and strength). These studies provide insight on improvement of vertebroplasty procedures. However, cement volume and location do not necessarily correlate well to mechanical property restoration. Other factors, most notably the amounts of vertebral damage present, play an important role in the restoration of vertebral stiffness and strength to undamaged levels. Few studies, if any, have systematically evaluated cement repair regimes as a function of vertebral damage level.

The aims of this study were to quantify the efficacy of vertebroplasty according to: (1) damage level and (2) cement quantity (fill) and modulus. Vertebral damage and vertebroplasty were simulated using a damage scheme (modulus reduction) and structural finite-element (FE) model of a T10 thoracic vertebral body. The results of this study will assist clinicians to further understand the biomechanics of vertebral cement augmentation, and will aid in the development of guidelines for vertebroplasty-specific bone cements.

## Methods

### FE model

A 1.8-mm thick, mid-sagittal μCT scan (μCT 80, Scanco USA, Inc., Wayne, PA) of a thoracic (T10) vertebral segment from an elderly (>65 years of age) female was used to construct a two-dimensional (2D), anatomically accurate structural FE model (Fig. 1). The anterior-posterior (A-P) depth and inferior-superior (Inf-Sup) height of the model were 24.8 mm (299 pixels) and 19.5 mm (235 pixels), respectively. Images were converted into 4-node isoparametric elements using custom MATLAB software (MathWorks, Natick, MA). The resulting FE model mesh had a spatial resolution of 83 μm/element and an element aspect ratio of 1:1.

Trabecular bone, intervertebral disc, and bone-marrow tissues elements were modeled as isotropic, linear elastic materials, with elastic modulus values of 10 GPa, 2.16 MPa, and 10 kPa, respectively [15, 19, 20, 21, 22]. Previous FE studies of trabecular bone structures have shown that the FE model results are relatively insensitive to Poisson ratio variations [31, 32], so a Poisson's value of 0.3 was assumed for all bone tissues (37828 elements). Disc (5261 elements) and marrow (20016 elements) tissues were idealized as low modulus solids with a Poisson's ratio of 0.3. Only a small portion of the disc annulus adjacent to the vertebral body (~1.5 mm) was incorporated in the FE model. Modeling of the in-

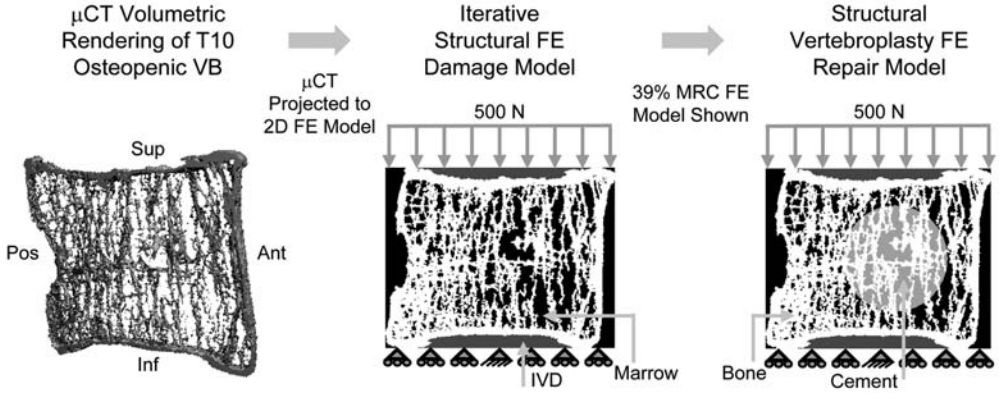


**Fig. 1** A μCT image of a T10 vertebral body was volumetrically rendered (*left*) and projected to create an anatomically accurate 2D structural finite element (FE) model (*center*). Load-induced damage of the vertebral body was simulated using a modulus reduction scheme (elasto-plastic modulus reduction; EPMR) [18, 19]. Simulation of vertebroplasty was then performed by replacing bone-marrow elements with cement elements (*right*). The resulting FE damage-repair model was uniformly loaded and simply supported. *IVD* intervertebral disc, *Marrow* bone marrow, *Bone* trabecular bone, *Cement* bone cement, *Pos* posterior, *Ant* anterior, *Sup* superior, *Inf* inferior

tervertebral disc annulus as a low modulus, compressible solid is consistent with the properties of a degenerative disc, and was intended to duplicate experimental test conditions used in a related study for model validation [19, 22]. A uniform compressive load ranging from 50 N to 500 N in 50-N increments was applied to a laterally constrained rigid plate located on the superior surface of the vertebral body. The inferior surface of the vertebral body was simply supported. Peak loads were chosen to represent the upright posture compressive body force acting at T10 for a 76.6-kg female [16, 17].

### Elasto-plastic modulus reduction scheme

A plane stress FE analysis was coupled with an elasto-plastic modulus reduction (EPMR) scheme [6, 19, 20, 21, 22]. In this scheme, modulus reduction is representative of diffuse damage accumulation within the trabecular bone tissue elements, and results in a decrease in the overall structural or apparent modulus of the vertebral body given by [19, 22].

$$d\sigma/d\varepsilon' = -\sigma_0\beta\left[-\tanh\beta^{-(m-1)/m} + \tanh\beta^{m+1/m}\right]\varepsilon'^{-1}$$

where:

$$\beta = \left[E_0\varepsilon'/\sigma_0\right]^m$$

In the above equation, E', $E_0$, $\sigma_0$ and $m$ are the tissue principal strain intensity, tissue modulus, ultimate stress asymptote, and damage accumulation exponent, respectively. The stress asymptote ($\sigma_0$= 159 MPa) and tissue modulus ($E_0$=10,000 MPa) were chosen to correspond to the strength and modulus of dense bone tissue (apparent density=1.9 g/cm$^3$) [14]. The damage accumulation exponent ($m$=4) was chosen based on experimental results used to validate the numerical model [19, 22]. After each increment of load, the principal strain intensity (difference in principal strains) for each element was used to calculate the element modulus reduction (if any); elements with a modulus reduction corresponding to bone marrow or lower were permanently assigned to the marrow modulus. Following each load step, the vertebral body apparent modulus was calculated as: $\sigma_a/\varepsilon_a$, where $\sigma_a$ is the apparent stress or applied load per unit area, and $\varepsilon_a$ is the apparent strain or change in vertebral body height divided by the undamaged inferior-superior vertebral height. As the load on the vertebral body increases, the ensuing $\sigma_a$–$\varepsilon_a$ behavior becomes non-linear and the apparent modulus of the vertebral body decreases. The EPMR scheme and two-dimensional, plane stress FE approach to study vertebral damage has been experimentally and numerically validated [19, 22].

### Vertebroplasty simulation

Four structural damage models corresponding to apparent modulus reductions of 19%, 33%, 60%, and 91% were used to simulate vertebroplasty repair (Table 1). Each of the structurally damaged FE models was analyzed using six different cement fill models (12%, 23%, 39%, 55%, 71%, and 100% marrow replaced by cement, MRC). The mid-sagittal placement of cement in these fill models is consistent with a parapedicular surgical approach. For these analyses, the cement elements replacing the marrow elements were assumed to be perfectly bounded to the adjacent bone elements and assigned an elastic modulus of 2.16 GPa, representative of PMMA [30]. A linear, plane stress, static (500 N) FE analysis was performed on each damage-repair model (30 total including undamaged) and the stress-strain results were compared to the undamaged vertebral body results. The principle outcome measures studied were the vertebral apparent modulus and element stress concentrations (element or tissue stress/apparent stress).

**Table 1** Vertebral stress-strain results obtained from elasto-plastic modulus reduction (EPMR) scheme

| Load iteration | Applied load (N) | Apparent stress (MPa) | Apparent modulus (MPa) | Modulus reduction (%) |
|---|---|---|---|---|
| 1 | 50 | 1.1 | 1132.8 | 0 |
| 2 | 100 | 2.2 | 1132.8 | 0 |
| 3 | 150 | 3.4 | 1131.1 | 0 |
| 4 | 200 | 4.5 | 1102.5 | 3 |
| 5 | 250 | 5.6 | 1074.8 | 5 |
| 6 | 300 | 6.7 | 1020.6 | 10 |
| 7 | 350 | 7.8 | 921.1 | 19 |
| 8 | 400 | 9.0 | 754.1 | 33 |
| 9 | 450 | 10.1 | 449.2 | 60 |
| 10 | 500 | 11.2 | 102.4 | 91 |

The influence of bone cement modulus on vertebral apparent modulus was examined by varying the cement modulus in the range of 1 GPa to 9 GPa. For these analyses, two vertebroplasty repair models (39% MRC and 100% MRC) were used at a vertebral damage level corresponding to a modulus reduction of 33%. Linear, plane stress, static (500 N) FE analyses were performed for each of the cement modulus varying models.

All of the numerical damage and repair preprocessing, solution, and post-processing analyses were performed using proprietary MATLAB programs (MathWorks, Natick, MA).

## Results

### EPMR scheme

The EPMR scheme produced a non-linear stress-strain response and a decrease in apparent modulus for apparent (applied) stresses greater than 5 MPa (Table 1 and Fig. 2). The last four loading increments corresponded to an apparent modulus reduction of 19%, 33%, 60% and 91%, in comparison with the undamaged apparent modulus (1132.8 MPa).

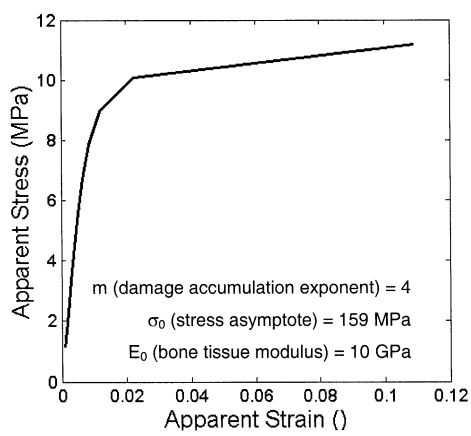


**Fig. 2** Non-linear stress-strain response of the T10 vertebral body predicted by the elasto-plastic modulus reduction (EPMR) scheme

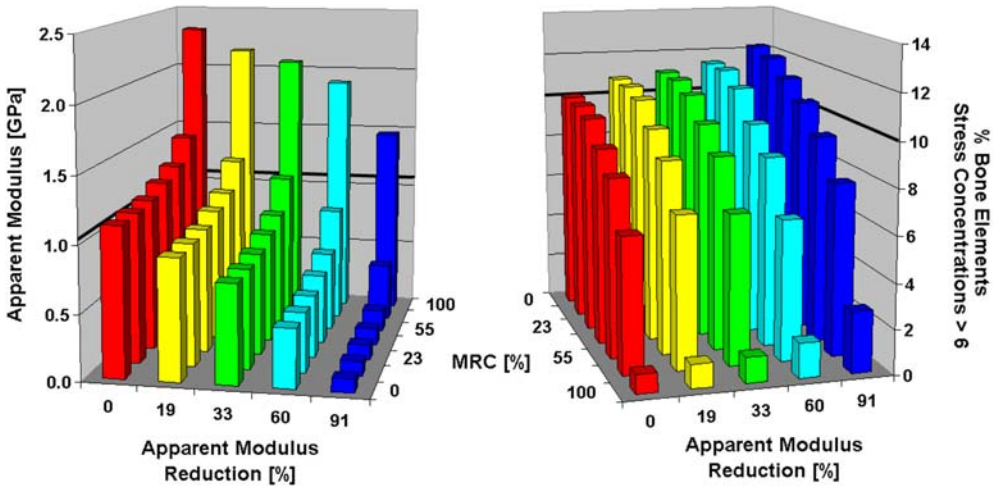


**Fig. 3** *Left* The T10 vertebral apparent modulus decreases with increasing amount of trabecular bone damage (apparent modulus reduction) and increases with increasing marrow replaced by cement (% MRC). *Right* Stress concentrations (% Bone Elements with Stress Concentrations >6) increase with increasing amount of trabecular bone damage and decrease with increasing marrow replaced by cement (% MRC). The *solid black line* shown is representative of the undamaged untreated vertebral model

Table 1 summarizes the applied load, apparent stress, apparent modulus, and percentage modulus reduction for all 10 EPMR loading iterations applied to the T10 vertebral body.

## Vertebroplasty simulation

Replacement of all bone-marrow elements by PMMA cement elements (100% MRC) resulted in a substantial increase in the apparent modulus for all damage levels investigated (Fig. 3, left column). In the undamaged vertebral body model, replacement of all marrow elements (100% MRC) resulted in a 106% increase in apparent modulus. Models with moderate damage (19% and 33% apparent modulus reduction) recovered to the undamaged apparent modulus following 71% MRC, whereas the most severely damaged model (91% apparent modulus reduction) required 100% MRC in order to restore the undamaged vertebral body apparent modulus. Vertebroplasty cement models (12%, 23%, or 55% MRC) were unable to restore the vertebral body apparent modulus to undamaged levels even in the least damaged model studied (19% apparent modulus reduction).

Application of the uniform compressive load prior to cement augmentation (0% MRC) of the vertebral body resulted in a substantial number of highly stressed bone elements (10% of bone elements with a stress concentrations >6) (Fig. 3, right column). Distribution of highly stressed elements followed a column-wise (superior-inferior) pattern within the cortical shell as well as along more centrally located trabeculae of the thoracic vertebral body (Fig. 4). The tissue stress concentrations, on average, across all bone elements, were two for the undamaged untreated vertebral body. Addition of PMMA cement (2.16 GPa modulus) altered the stress transfer within the vertebra and was effective in reducing the number of highly stressed elements in both the undamaged and damaged models. Complete marrow replacement with PMMA cement resulted in a 91% reduction in bone stress concentrations greater than six in the undamaged model (from 10% for the undamaged-untreated to 0.9% for the undamaged completely filled model) (Table 2, Fig. 3). A decrease in the apparent modulus of the vertebral body resulted in an increase in the number of highly stressed bone elements (22% for the severely damaged or 91% model). Compared with the undamaged, 0% MRC model, three of the four damage levels (19%, 33%, and 60% reduction in apparent modulus) had fewer highly stressed elements after 39% cement augmentation (refer to Fig. 3, right column). In the most severely damaged model (91% modulus reduction), 55% of the marrow elements needed to be replaced by PMMA cement to reduce the highly stressed elements below that of the undamaged untreated (0% MRC) model. In this severely damaged model, highly stressed elements decreased from 12.2% (0% MRC model) to 2.7% (100% MRC model) (refer to Fig. 3 and Fig. 4). In comparison with the undamaged untreated (0% MRC) model, the 91% damage model with complete cement replacement (100% MRC) resulted in a 73% decrease in the number of highly stressed elements. The 91% damage model also exhibited a much more uniform stress distribution following augmentation relative to the similar damage untreated (0% MRC) vertebra (refer to Fig. 4).

The influence of cement modulus variations on vertebral apparent modulus is summarized in Fig. 5. Variations in cement modulus had no appreciable effect on the recovery of vertebral apparent modulus to undamaged levels for simulations of partial cement fill (39% MRC). There was a 16.2-MPa (2%) increase in vertebral apparent modulus when the cement modulus increased from 1 GPa to 9 GPa (39% MRC model). For complete cement fill, however, a PMMA cement modulus produced an approximate 2-fold increase (82%) in vertebral apparent modulus compared with the undamaged vertebral body. The vertebral apparent modulus increased 1195 MPa (69%) when the cement modulus was increased from 1 GPa to 9 GPa, corresponding to over a 2.5-fold increase relative to the

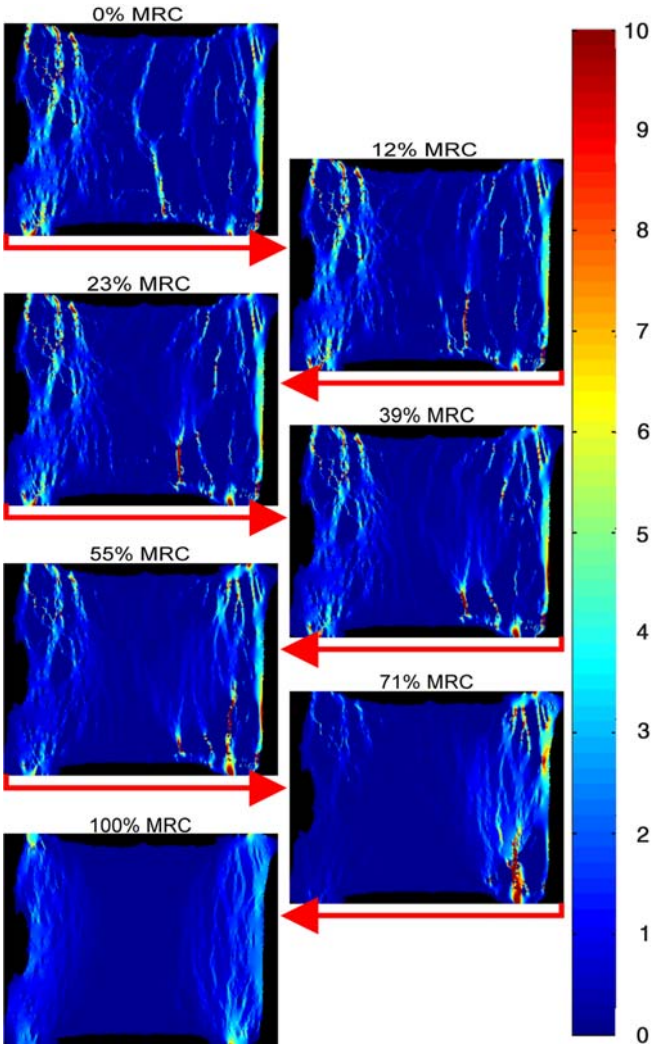


**Fig. 4** Tissue element stress concentrations (tissue stress/apparent stress) decrease with increasing marrow replaced by cement (% MRC). Stress concentrations are color coded over a range from 0 (low) to 10 (high). Results shown are for the 91% apparent modulus reduction damage model

**Table 2** Summary of vertebral stress-strain changes following simulated vertebroplasty. Results for 100% MRC polymethylmethacrylate (PMMA) fill model. PMMA modulus =2.16 GPa

| Modulus reduction model (%) | Apparent modulus (% Δ relative to undamaged vertebral body) | Mean bone tissue stress concentration (% Δ relative to undamaged vertebral body) | Stress concentrations >6 (% total bone elements) |
|---|---|---|---|
| 0 | 105.6 | 20.3 | 0.9 |
| 19 | 90.1 | 20.4 | 1.1 |
| 33 | 82.4 | 20.8 | 1.1 |
| 60 | 67.5 | 21.5 | 1.6 |
| 91 | 29.8 | 22.1 | 2.7 |

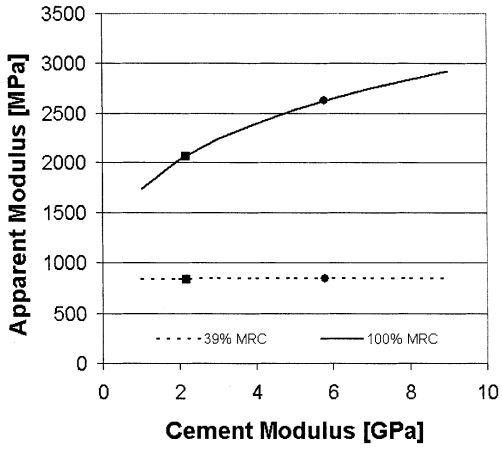


**Fig. 5** Relationship between vertebral apparent modulus and cement modulus for partial (39% MRC) marrow replacement with cement (*dashed line*) and complete (100% MRC) marrow replacement with cement (*solid line*). The *square* and *circle* symbols show results representative of PMMA ($E_{cement}$=2.16 GPa) and Orthocomp ($E_{cement}$=5.8 GPa), respectively. Results shown are for the 33% apparent modulus reduction damage model

undamaged state. Similar to apparent modulus, variations in cement modulus had no appreciable effect on further reducing the amount of highly stressed elements for the partial cement fill model (39%MRC). Although the augmentation of cement having a modulus value of 1 GPa resulted in a 13% reduction in highly stressed elements relative to the initial untreated, undamaged model, the 9 GPa cement modulus model presented no further appreciable difference (15% reduction compared to initial). In contrast, the complete cement fill model resulted in approximately a 5-fold decrease in highly stressed elements for a cement modulus of 1 GPa, and a 16-fold decrease using a cement modulus of 9 GPa compared with the initial untreated vertebral body.

## Discussion

Following vertebral compressive fracture, there is a substantial reduction in mechanical strength and stiffness [2, 3, 4,13, 24, 25, 33]. In this study, a microstructural FE model and microdamage scheme [19, 22] were used to simulate the effects of parapedicular vertebroplasty on thoracic vertebral body mechanical properties. The FE method provides a means to identify stress concentrations and the manner in which stresses are distributed within the vertebral body.

The microstructural, plane stress FE analysis and EPMR damage scheme used in this study reproduces the experimental non-linear stress-strain behavior of the thoracic vertebral body [19, 22]. However, there are some inherent limitations of the numeric analysis used to simulate verte-

bral damage and repair (vertebroplasty). First, the results of this study are limited to a single human thoracic vertebra following vertebroplasty cement augmentation and should not be generalized to other vertebrae or other cement augmentation procedures, such as kyphoplasty. Second, a uniform compressive load was used to represent the loading environment of the thoracic vertebral body, when in fact the vertebral body experiences a non-uniform, complex loading profile. A uniform loading condition was deemed sufficient however, since the focus of this study was to examine relative changes in mechanical behavior following cement augmentation [24]. The support and loading boundary conditions, chosen to represent our experimental tests, are also limiting in that they may be predominantly responsible for the load transfer patterns reported along the vertebral cortex. Moreover, the analysis does not take into account structural influences of increased vertebral stiffness from cement augmentation on neighboring vertebral bodies and/or pressure changes in the intervertebral disc. Increasing the stiffness of the fractured vertebral body may, in fact, compromise the structural stability of adjacent vertebra [1, 5, 11, 29]. Cement augmentation has been reported to increase both the pressure in the intervertebral disc and endplate deflection of adjacent vertebrae, and some authors speculate that vertebrae adjacent to augmented segments may be more susceptible for fracture [1, 29]. Other factors, such as thermal damage to trabecular bone tissue associated with PMMA cement polymerization have not been modeled, and parapedicular vertebroplasty repair was simulated using simple two-dimensional cement geometry. Finally, projection of the three-dimensional architecture of the vertebral body to two-dimensions created a more dense vertebral structure than would be expected for an osteoporotic vertebra. Hence, our FE results may have overestimated the apparent (structural) stiffness of the thoracic vertebrae.

One benefit for both continuum and microstructural FE modeling relative to experimental studies is that variations between the shape and material properties of human vertebral bodies can be eliminated, thus allowing parametric studies to be performed to determine the influence or sensitivity of various parameters. The two-dimensional structural FE model presented here retains essential elements of the planar trabecular bone structure, allows for determination of internal trabecular bone tissue stresses, and enables parametric evaluation of the cement augmentation process (quantity and modulus of cement). These are important for biomechanical and clinical understanding of vertebroplasty. Results presented relative to the undamaged vertebral body also aid in characterizing and normalizing the outcome measures. Moreover, structural models can be used to visualize regions of bone tissue damage and structural fragility. Using the EPMR modeling approach, which has been shown to predict areas of diffuse damage experimentally for the thoracic vertebra [19, 22], can be a valuable numerical tool in bone tissue damage mechanics.

Our numerical simulation results indicate that recovery of apparent modulus (stiffness) can be achieved by partial PMMA cement fill of the vertebral body for stiffness reductions as high as 33%. Between 19% and 33% stiffness reduction, the cement fill required to restore vertebral stiffness to within 15% of the undamaged stiffness ranged from 23% to 71% MRC (15–30% total vertebral body volume). This is higher than predictions of previous numerical studies, which report that a 2% PMMA fill (unipedicular or bipedicular) of the total L1 vertebral volume was required to restore the damaged vertebral body stiffness (24% modulus reduction) to within 15% of the undamaged stiffness level [24]. In this previous numerical study, a 14% PMMA fill (unipedicular or bipedicular) of the L1 vertebral volume was required to increase stiffness above the undamaged level. Differences between this and the current study include the numerical damage scheme, different tissue discretization approaches (2D structural versus 3D continuum FE analyses), PMMA cement location (parapedicular versus uni- and bi-pedicular) and the vertebral level investigated. In particular, continuum FE analyses do not discretely reproduce the structural elements of the trabecular bone tissue in the same manner as was possible in the current study. Our findings indicate that a PMMA fill of 71% MRC (30% of the total vertebral body volume) is required for complete stiffness recovery of moderately damaged (19–33% apparent modulus reduction) thoracic vertebrae.

A number of ex-vivo biomechanical studies have examined the compressive stiffness of lumbar and thoracolumbar vertebral bodies following vertebroplasty [2, 3, 4, 25, 33]. Experimental results presented by Belkoff and colleagues [3] suggest that complete PMMA cement fill (8 ml) is required to restore the structural stiffness of damaged thoracic vertebral bodies to approximately 90% of the undamaged structural stiffness. Partial PMMA cement fill (2 ml) resulted in restoration of approximately 50% of the undamaged structural stiffness. In their study, a simulated compression fracture was produced by loading the vertebrae to the point of failure defined as a precipitous decrease in load with increasing compression of the vertebral body. The reduction in vertebral stiffness following fracture was not reported, so it is not possible to directly compare their experimental results to our numerically derived results. However, their bipedicular partial fill (nominally 25% of total vertebra volume) results compare favorably with our simulations for a centrally located PMMA cement fill (55% MRC or 27% of total vertebral volume) following a 33% reduction in apparent modulus. Experimental results reported by Tohmeh and colleagues [33] indicated that unipedicular (6 ml) and bipedicular (10 ml) PMMA cement repair of compression damaged lumbar vertebral bodies restored the stiffness to near undamaged levels. Examination of the data presented by these authors indicated that the mean damage level corresponded to a 37% reduction in stiffness. This corresponds well with our

partial fill PMMA vertebroplasty simulations (71% MRC or 30% of the total vertebral volume) at a modulus reduction of 33%.

Noteworthy was our finding that variations in cement modulus had no appreciable effect on the vertebral apparent modulus for partial cement augmentation (39% MRC or 21% of total vertebral body volume) of the moderately damaged (33% modulus reduction) thoracic vertebra. This finding is similar to the experimental results of Belkoff et al. [3], but differs from previous experimental work by this group [2]. In the previous study, they noted that bipedicular augmentation (8 ml) using a high modulus (5.8 GPa), composite material (Orthocomp, Malvern, PA) was more effective than PMMA (Simplex-P, Stryker-Howmedica-Osteonics, Rutherford, NJ) augmentation (8 ml). They found that Orthocomp restored the stiffness of lumbar vertebrae to initial, undamaged levels, whereas Simplex-P restored the stiffness to only 62% of the initial value. The latter stiffness restoration corresponds well with our findings (74% stiffness recovery for partial parapedicular PMMA augmentation, 39% MRC, and moderate damage, 33% modulus reduction). However, increasing the cement modulus up to 6 GPa did not increase the apparent modulus at this damage and cement fill level. Both Simplex-P and Orthocomp restored the strength of the vertebral bodies, but Belkoff and associates did not report the relative amount of initial damage. Moreover, fracture was not a result in some of the experimental compression specimens tested by this group. In the latter study [3], the stiffness differences between 8 ml bipedicular Simplex-P and Orthocomp augmentation of thoracic vertebrae were not appreciable (92% and 97% of the undamaged stiffness for Simplex-P and Orthocomp, respectively). More explicit comparisons to these and other experimental studies examining different bone cements [4, 25], however, are not possible, since the degree of damage produced in our numerical simulations may not be similar to the damage produced in their experimentally simulated compression fractures.

Our EPMR scheme and the uniform loading conditions produced stress concentrations and diffuse damage in the vertebral cortical shell and in more central regions of the thoracic vertebrae. The results of our study indicated that changes in vertebral apparent modulus (stiffness) are more sensitive to the amount of cement than to the cement modulus. An explanation for this observation may be the fact that damaged and undamaged trabecular bone tissue adjacent to the cement fill region was subjected to increased stress. Highly stressed trabecular bone regions will experience increased deformation, which counteract the increase in stiffness and reduced stresses in the cement-encapsulated trabecular bone regions (Fig. 6). In contrast, complete fill of the vertebral body with cement encapsulates all trabeculae and leaves no unsupported bone elements. In the case of complete PMMA cement fill, we found that the number of highly stressed trabeculae decreased dramatically (over 4-fold) relative to the untreated, microdamaged segment, which implies that the vertebral strength has increased substantially. Based on the simulations performed, however, we cannot directly infer the effects of PMMA cement augmentation on vertebral strength. Experimental studies have reported as much as a 2- to 3-fold increase in thoracolumbar vertebral strength following bipedicular PMMA cement augmentation (6–10 ml or nearly filled) [2, 25, 33]. Additional work is needed to characterize the effects of cement augmentation (vertebroplasty, kyphoplasty) on the stiffness, strength,

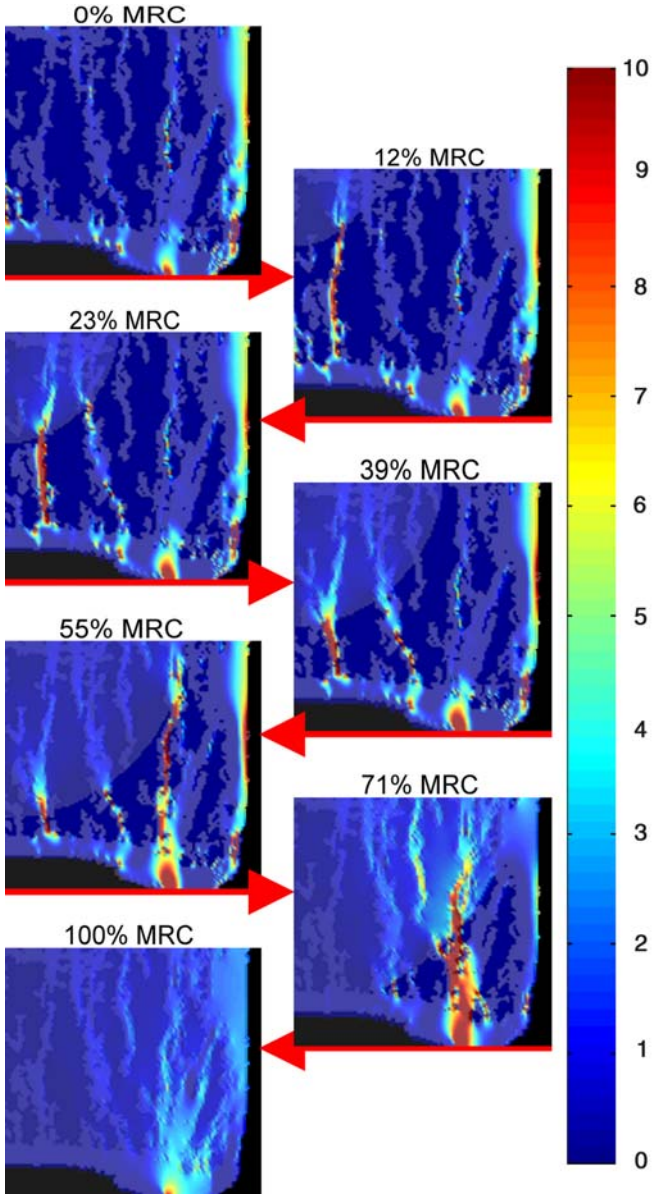


**Fig. 6** Magnified anterior-inferior regions, for the 91% apparent modulus reduction damage model, around the cement augmentation showing the increased tissue stress concentrations around the boundaries of the cement. Stress concentrations are color coded over a range from 0 (low) to 10 (high)

and post-treatment stress-strain response of both treated and adjacent segment vertebrae.

Ultimately, restoration of vertebral mechanical properties (strength and modulus) is dependent on a number of factors including bone density, damage level, and cement quantity, modulus and placement. These factors, together with the complexity of vertebral geometry and material properties, suggest that sophisticated computational tools and algorithms will need to be developed to predict the quantity and placement of cement required to restore vertebral strength and stiffness. Numerical simulations using anatomically precise 2D and 3D vertebral geometry derived from computed tomography images are becoming more practical and may prove to be valuable for clinical management of vertebral compression fractures and tumors. Such tools may yield insight for optimal cement placement in areas that are predicted to undergo damage.

## Conclusion

A microstructural FE model and modulus reduction scheme was used to simulate vertebroplasty of a damaged thoracic vertebra. Of clinical interest was the finding that complete cement fill was required to restore the apparent modulus of highly damaged vertebral bodies. In the case of moderately damaged vertebrae, an approximately 70% cement fill (30% of the total vertebral body volume) is recommended to completely restore stiffness to intact or undamaged levels. More severely damaged segments should be completely filled with cement. In the development of guidelines for vertebroplasty-specific bone cements, our results also suggest that cement modulus is only important when the vertebral body is completely filled with cement.

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