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ORIGINAL ARTICLE

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Spinal loads after osteoporotic vertebral fractures treated by vertebroplasty or kyphoplasty

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Abstract Vertebroplasty and kyphoplasty are routine treatments for compression fractures of vertebral bodies. A wedge-shaped compression fracture shifts the centre of gravity of the upper body anteriorly and generally, this shift can be compensated in the spine and in the hips. However, it is still unclear how a wedge-shaped compression fracture of a vertebra increases forces in the trunk muscle and the intradiscal pressure in the adjacent discs. A nonlinear finite element model of the lumbar spine was used to estimate the force in the trunk muscle, the intradiscal pressure and the stresses in the endplates in the intact spine, and after vertebroplasty and kyphoplasty treatment. In this study, kyphoplasty represents a treatment with nearly full fracture reduction and vertebroplasty one without restoration of kyphotic angle although in reality kyphoplasty does not guarantee fracture reduction. If no compensation of upper body shift is assumed, the force in the erector spine increases by about 200% for the vertebroplasty but by only 55% for the kyphoplasty compared to the intact spine. Intradiscal pressure increases by about 60 and 20% for the vertebroplasty and kyphoplasty, respectively. In contrast, with shift compensation of the upper body, the increase in muscle force is much lower and increase in intradiscal pressure is only about 20 and 7.5% for the vertebroplasty and kyphoplasty, respectively. Augmentation of the vertebral body with bone cement has a much smaller effect on intradiscal pressure. The increase in that case is only about 2.4% for the intact as well as for the fractured vertebra. Moreover, the effect of upper body shift after a wedge-shaped vertebral body fracture on intradiscal pressure and thus on spinal load is much more pronounced than that of stiffness increase due to cement infiltration. Maximum von Mises stress in the endplates of all lumbar vertebrae is also higher after kyphoplasty and vertebroplasty. Cement augmentation has only a minor effect on endplate stresses in the unfractured vertebrae. The advantages of kyphoplasty found in this study will be apparent only if nearly full fracture reduction is achieved. Otherwise, differences between kyphoplasty and vertebroplasty become small or vanish. Our results suggest that vertebral body fractures in the adjacent vertebrae after vertebroplasty or kyphoplasty are not induced by the elevated stiffness of the treated vertebra, but instead the anterior shift of the upper body is the dominating factor.

Keywords Cement augmentation · Vertebroplasty · Kyphoplasty · Finite-element modelling · Intradiscal pressure

Introduction

Painful vertebral osteoporotic compression fractures are extensively treated by vertebroplasty or kyphoplasty. Vertebroplasty provides stabilization and pain relief often without deformity improvement. However, through specific patient positioning on the operating table, height restoration is possible for recent fractures. Vertebroplasty is performed by percutaneous injection of polymethylmetacrylate (PMMA) into the fractured vertebral body through one or two bone biopsy needles. Since PMMA is forced into the cancellous bone matrix, high pressure and runny cement are required, with the risk of leakage. A total of 1–4 ml per side can usually be inserted [5]. Kyphoplasty was designed to address the kyphotic deformity and to realign the spine. It involves a percutaneous insertion of an inflatable balloon tamp into the vertebral body under image guidance. When inflated with liquid, the balloon compacts the cancellous bone and re-expands the body. Two balloons are commonly used together in the operation. After deflation, the remaining cavity facilitates the controlled placement of thick PMMA under low pressure with low risk of cement leakage. Approximately 2–6 ml PMMA per side can usually be inserted [5, 8]. From the radiographic data of patients with vertebral compression fractures after the kyphoplasty treatment, Ledlie and Renfro [11] found that the midline height was increased from 65% of the preoperative value to 90% at 1 month post-treatment. In vertebral bodies with 15% or more height loss, Garfin et al. [5] reported that the average midline height improved from $64 \pm 12\%$ of the intact height to $90 \pm 12\%$ after treatment. Such height restorations are only achievable in fresh fractures. In old fractures, the height increase is much lower. Potential height restoration in fresh fractures and decreased risk of cement leakage are the main advantages of kyphoplasty treatment over vertebroplasty treatment [5, 8, 16]. However, kyphoplasty does not guarantee fracture reduction. The mean kyphotic angle restoration in many clinical cases is low and nearly the same for both kyphoplasty and vertebroplasty.

Several groups [2, 12, 14, 23, 27] have studied the effects of bone cement volume and distribution on vertebral stiffness after injection of PMMA. They found that vertebral stiffness and strength increase with higher PMMA volume while actually only a small amount of PMMA is necessary to restore strength and stiffness.

Strength and structural stiffness of paired osteoporotic two-vertebra functional spinal units (FSUs) were studied by Berlemann et al. [3]. One of each pair was augmented with PMMA in the caudal vertebra, while the other served as an untreated control. Compared with the controls, the ultimate failure load of FSUs with cement injection was lower.

Villarraga et al. [28] created a finite element model of an FSU without the posterior elements and simulated a kyphoplasty. They predicted only a slight effect of kyphoplasty treatment on the stress magnitudes and distributions in adjacent vertebrae. Furthermore, they found that the effect of cement modulus on the stresses in bone and cement is negligible.

The effects of bone cement placement, volume, and bone density on biomechanical recovery and fracture risk were analytically investigated by Sun and Liebschner [27]. They predicted that prophylactic vertebroplasty is effective in reducing fracture risk.

Polikeit et al. [17] modelled an osteoporotic L2–L3 FSU to study the effect of cement augmentation on the load transfer. They reported that augmentation increased the pressure in the nucleus pulposus and the deflection of the adjacent endplate. The load transfer in adjacent vertebrae was altered by the treatment. Their findings also support the hypothesis that rigid cement augmentation may promote the subsequent collapse of adjacent vertebrae.

In a finite element study, Baroud et al. [1] found that infiltrating osteoporotic cancellous bone with bone cement reduced the inward bulge of the endplates at the augmented vertebra to 7% of its value before the augmentation. This infiltration also stiffened the intervertebral joint by approximately 17%, increased the intervertebral pressure by 19% and extended the inward bulge of the endplate adjacent to the augmented vertebral body by 17%. They postulated that this increase was the cause of adjacent fractures occasionally encountered after vertebroplasty treatment [1, 3, 7].

In a recent study, Rohlmann et al. [23] used a finite element model of the lumbar spine and simulated a vertebroplasty in L3. They found that the bulge of the vertebral body endplate and thus intradiscal pressure depends strongly on the grade of osteoporosis in the vertebral body. The influence of the amount and elastic modulus of bone cement on intradiscal pressure was small.

A wedge-shaped vertebra compression fracture also alters the curvature of the spine. This kyphotic deformation increases the lever arm of the centre of gravity relative to the fractured vertebra. The increase of the resultant flexion moment is a function of the wedge angle and the original curvature of the Spine. White and Panjabi [29] used a simplified model to calculate the relative increase of the flexion moment due to the wedge-shaped vertebra. The predicted flexion moment depended strongly on the wedge angle and the position of the fractured vertebra relative to the centre of gravity of the upper body.

In finite element studies dealing with vertebroplasty [1, 12, 17, 27, 28] an FSU was normally loaded in compression and a load change due to a wedge-shaped vertebral compression fracture was not taken into

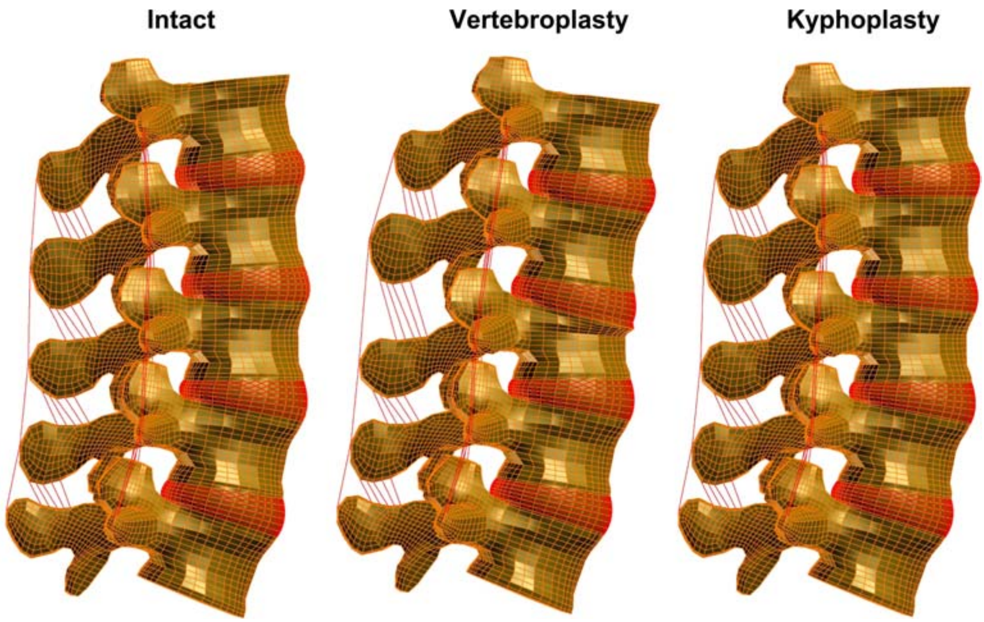

Fig. 1 Finite element models of the intact lumbar spine (*left*) the vertebroplasty model (*middle*) and the kyphoplasty model (*right*). Wedge-shaped fracture was assumed in the L3 vertebral body

account. We hypothesise that a wedge-shaped fracture increases the necessary muscle force for balancing the spine as well as the disc pressure.

The aims of the present study were (1) to estimate the forces of the muscles during standing for an intact lumbar spine, as well as after vertebroplasty and kyphoplasty and (2) to determine intradiscal pressure and maximum von Mises stress in the vertebral endplates before and after cement augmentation.

Methods

A three-dimensional, non-linear finite element model of the osseoligamentous lumbar spine (L1 to L5) was used (Fig. 1). The model consists of about 64,000 hexaedral elements and has more than 184,000 degrees of freedom. The annulus fibrosus of the intervertebral disc was modelled using volume elements for the ground substance and spring elements for the fibres. There are seven layers of fibres under alternating angles of 30° and 150° relative to the mid-plane of the disc. Their stiffness increases from the centre to the outer border. Incompressible fluid elements were used to simulate the nucleus pulposus. All seven ligaments of the lumbar spine were included in the model represented by spring elements with a non-linear stress-strain-behaviour and only able to transmit tensile forces. The material properties of the different tissues (Table 1) were taken from the literature. The facet joints had a gap of 0.5 mm and could only transmit compression. The pre- and postprocessor PATRAN (MSC Software, Marburg, Germany) and the finite element program ABAQUS, version 6.4 (Abaqus, Inc, Providence, RI, USA) were used for these nonlinear analyses.

Intact model

The force in the m erector spinae and the intradiscal pressure were determined for the intact lumbar spine. A prophylactic augmentation of an osteoporotic vertebral body is sometimes discussed, especially for a vertebra adjacent to a fractured one. Therefore, the effect of 6 ml PMMA augmentation of an intact osteoporotic L3 vertebral body was also studied. The material properties of PMMA are given in Table 1.

Table 1 Material properties used in this study

Material	Elastic modulus (MPa)	Poisson‘s ration (-)	Reference	Element type
Cortical bone	10,000	0.3	[6, 26]	8-node Hex
Cancellous bone	50	0.2	[6, 24, 26]	8-node Hex
Posterior elements	3,500	0.25	[22, 25]	8-node Hex
Annulus ground substance	3.15	0.45	[6, 22]	8-node Hex
Nucleus pulposus	Incompressible			Fluid
PMMA	3,000	0.41	[17]	8-node Hex

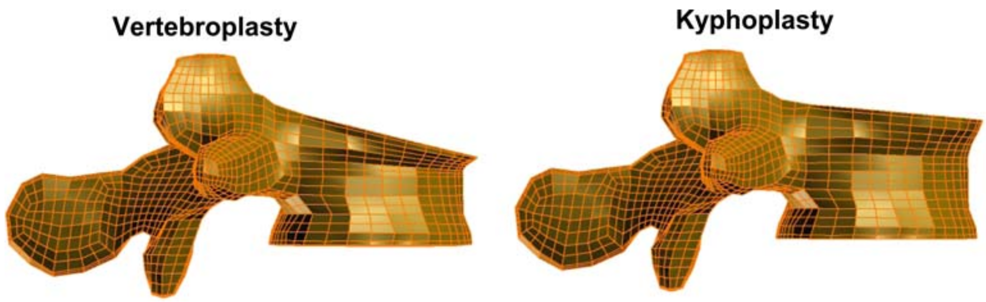

Fig. 2 Element meshes of the L3 vertebra. Compared to the intact vertebra, the anterior vertebral body height was reduced by 35% in the vertebroplasty model (*left*) and 10% in the kyphoplasty model (*right*)

Vertebroplasty model

A wedge-shaped L3 vertebral body was assumed in the vertebroplasty model. The vertebral body height was reduced by 35% of the original height on the anterior side while the posterior side remained unchanged (Fig. 2). Due to the wedge shape, the position of the centre of gravity (CoG) of the upper body moved anteriorly, and a higher force in the erector spinae was required to achieve equilibrium. The simulated volume of PMMA in the L3 vertebral body was 4 ml with symmetrical distribution. For comparison, a fractured L3 vertebral body without PMMA augmentation was also studied. In this study the vertebroplasty model represents no fracture reduction.

Kyphoplasty model

For the kyphoplasty model it was assumed that the anterior height of the wedge-shaped L3 vertebral body was corrected to 90% of the original height (Fig. 2). Thus, in this study, the kyphoplasty model represents a case of nearly full fracture reduction. The amount of PMMA inserted in the L3 vertebra was 6 ml to account for the larger volume of the vertebral body compared to that of the vertebroplasty model. A vertebral body height restoration without infiltration of bone cement commonly creates an unstable situation. Thus a kyphoplasty model without PMMA augmentation was not investigated.

Loading

The model was loaded with the upper body weight (260 N), a central follower load (200 N) to account for the local muscle forces [15, 20] and a force in the erector spinae or rectus abdominis (Fig. 3). The lever arms relative to the disc centre of erector spinae and rectus abdominis were 40 and 153 mm, respectively, and the direction of the muscle forces was approximately parallel to the lumbar spine [31]. The method to estimate the muscle forces for standing and different inclinations of the spine in the sagittal plane has been described in detail by Zander et al. [32] and Rohlmann et al. [19]. A given flexion angle of the lumbar spine was achieved by adjusting the muscle forces. The erector spinae represents the dorsal muscles and creates an extensional moment while the rectus abdominis is a ventral muscle that creates a flexional moment. No co-contraction was

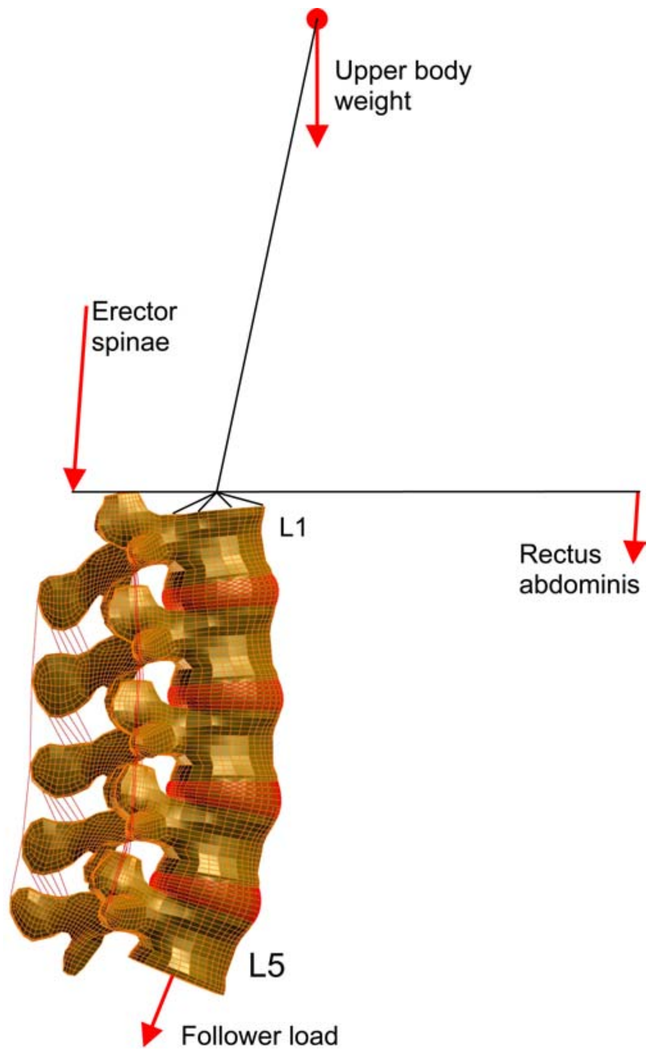

Fig. 3 Schematic sketch of the loads on the lumbar spine

assumed. In this study, the loading case 'standing' was investigated. After studying the intact model, the muscle forces in the erector spinae were determined for the vertebroplasty and kyphoplasty models and the stresses in different structures were calculated. The applied loads cause an axial reaction force at the L3 level for the intact, vertebroplasty and kyphoplasty models of 623, 956 and 715 N, respectively. Compared to the intact model, this is an increase of 53% for the vertebroplasty and 15% for the kyphoplasty model.

Compensation of upper body CoG shift

Due to a wedge-shaped vertebral body the CoG of the upper body moves anteriorly. This would require a higher muscle force in the erector spinae to achieve equilibrium at the thoraco–lumbar junction. To achieve an upright body position and in order to reduce the energy consumption, a compensation of the anterior shift of the upper body is necessary. In principle, such compensation can occur in the hips, in the lumbar spine and in the thoracic spine. These three modes were studied separately in this study although the compensation of CoG shift is probably a combination of two or all three modes. Only the static situation after full compensation is analysed here. The muscle forces for moving the upper body in the desired position are not considered in this study.

Compensation in the hips

The complete model was rotated backwards in the sagittal plane around the centre of the hips until the anteroposterior (AP) position of the upper body CoG relative to the hip joints is the same as in the intact model. However, in the vertebroplasty model, the upper body weight had a greater lever arm to the lumbar region than in the intact one. This resulted in higher forces in the erector spinae so that the resultant axial forces at the L3 level was 720 N for the vertebroplasty model. That is 16% higher than for the intact model and 33% lower than for the uncompensated model.

Compensation in the lumbar spine

The lumbar spine was extended until the angle between the upper L1 and lower L5 vertebral endplate was the same as in the intact model. Here the CoG of the upper body relative to the L1 vertebra was the same as in the intact model. But this compensation required deformations of the intervertebral discs and a higher force in the erector spinae. The axial reaction force at the L3 level was 706 N, which is 13% higher than for the intact model.

Compensation in the thoracic spine

Compensation in the thoracic spine was accomplished by backward bending of the thoracic region of the spine alone to the same AP position of upper body CoG relative to the L1 vertebra as in the intact model. The lever arm of the upper body weight for the other vertebrae and the necessary compensation force in the erector spinae was greater for this compensation method than in the intact model. The axial reaction force at the L3 level was the same (706 N) as for the compensation in the lumbar spine.

Results

The force in the erector spinae, necessary to balance the body weight during standing, drastically increased after a wedge-shaped vertebral body fracture if the upper body shift is not compensated. Compared to the intact model, the force increases by about 200% for the vertebroplasty while it increases by only 55% for the kyphoplasty (Fig. 4).

Compensation of upper body shift lowers the force in the erector spinae considerably (Fig. 5). This is the case for all the three compensation modes studied. Force reduction is more pronounced in the vertebroplasty model than in the kyphoplasty one. In the vertebroplasty model, compensation in the thoracic spine leads to the lowest muscle force while in the kyphoplasty model the differences between the different compensation modes are negligible. The hypothesis that a wedge-shaped fracture increases the muscle force required for balancing the lumbar spine is therefore corroborated.

The higher muscle force in vertebroplasty and kyphoplasty induces higher intradiscal pressures if the upper body shift is not compensated (Fig. 6). Compared to the intact model, the maximum pressure increase for the vertebroplasty model with and without PMMA augmentation is nearly 60%. As expected, the pressure increase in the kyphoplasty model (about 20%) is less than in the vertebroplasty model.

Augmentation of the L3 with bone cement increases intradiscal pressure in the discs adjacent to L3 vertebra in the intact and in the vertebroplasty model by less than 2.4%. Thus, the increase due to cement augmentation is much smaller than due to the anterior shift of the upper body.

The intradiscal-pressure increase in the vertebroplasty model is reduced at all levels of the lumbar spine due to compensation of upper body shift (Fig. 7). Compensation in the lumbar spine causes the lowest reduction compared to the uncompensated situation. But even after upper body shift compensation intradiscal pressure is still between 15 and 22% higher than for the intact spine. In comparison, the increase due to cement

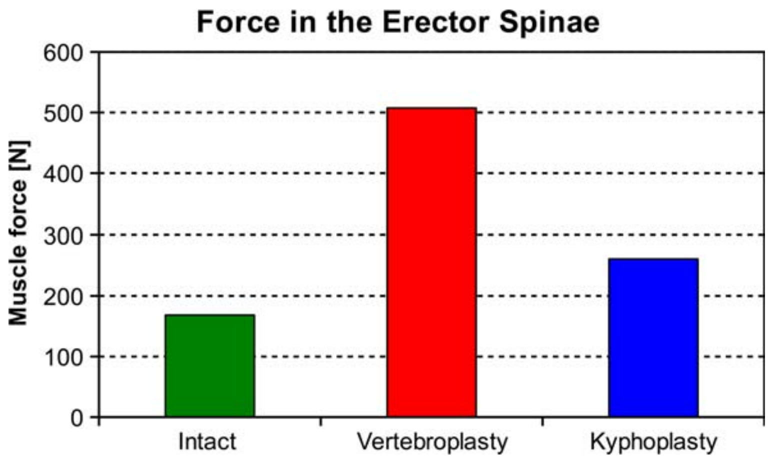

Fig. 4 Force in the erector spinae during standing for the different uncompensated models

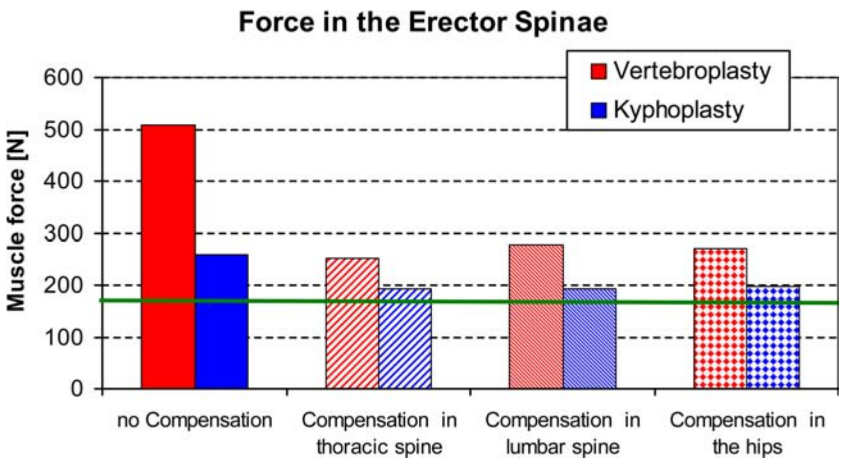

Fig. 5 Effect of upper body shift compensation on the force in the erector spinae. The *green horizontal line* at 168 N represents the muscle force for the intact model

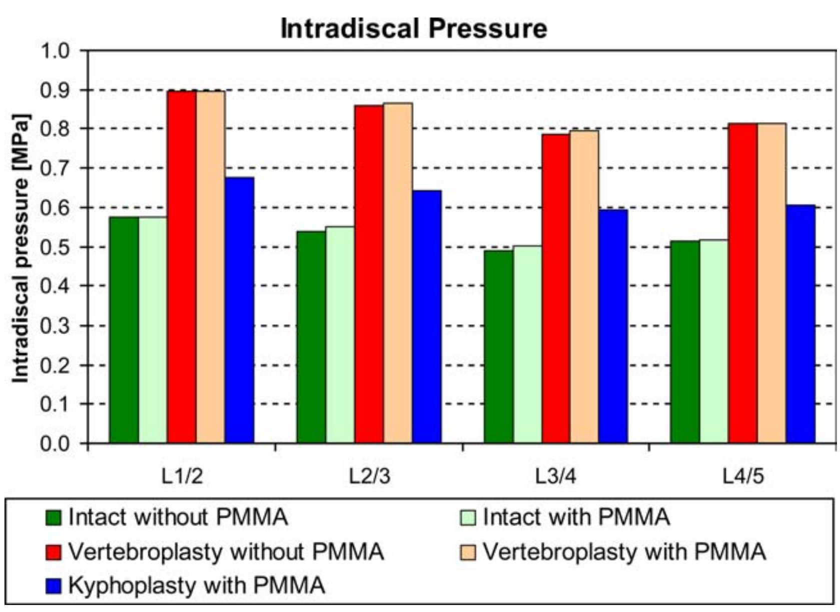

Fig. 6 Intradiscal pressure in the intact, vertebroplasty and kyphoplasty models. For the intact and vertebroplasty model pressure values are shown before and after insertion of bone cement. No upper body shift compensation was assumed

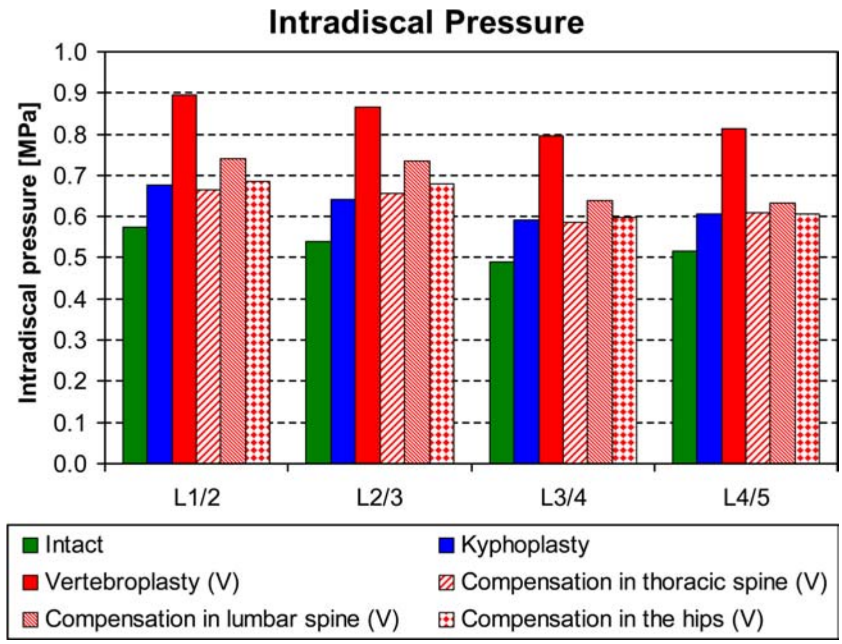

Fig. 7 Effect of different compensations on intradiscal pressure for the vertebroplasty model. For comparison, the pressures of different uncompensated models are also given. For all models, cement augmentation of L3 was assumed

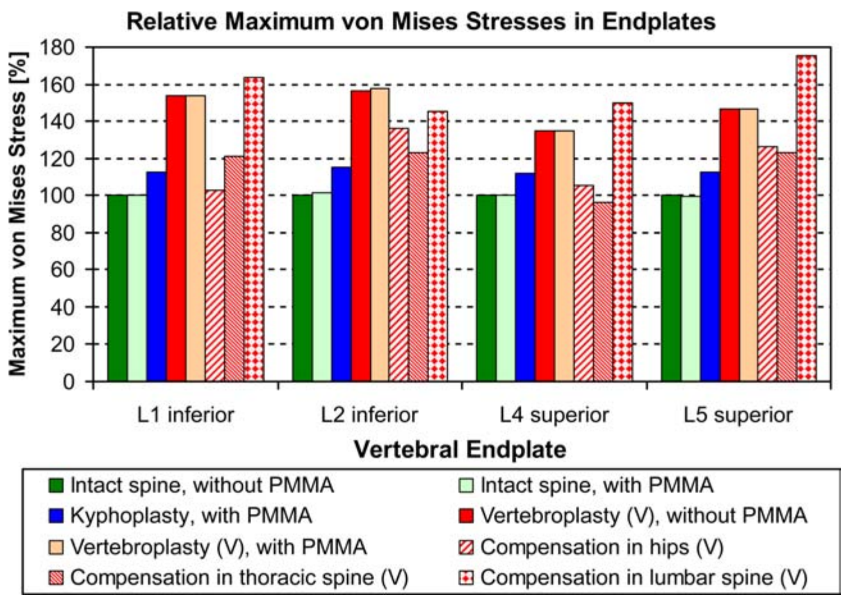

Fig. 8 Maximum von Mises stresses in the vertebral endplates facing the fractured L3 vertebra. The maximum stress for the intact lumbar spine was set to 100% and the values for the other cases were related to that stress value. The stresses for upper body shift compensation are shown for the vertebroplasty (*V*) model

augmentation is only 2.4%. In the kyphoplasty model, the predicted intradiscal pressure after compensation is between 2.5 and 7.4% higher than in the intact model. The hypothesis that a wedge-shaped vertebral body fracture increases intradiscal pressure is also corroborated.

Related to the intact lumbar spine, the maximum von Mises stresses in the vertebral endplates of the unfractured vertebrae are increased after kyphoplasty (up to 15%) and after uncompensated vertebroplasty (up to 58%) (Fig. 8). Upper body shift compensation in the hips and in the thoracic spine reduces the maximum stress while compensation in the lumbar spine mostly increases the maximum stress in the vertebral endplates. Injection of PMMA has only a minor effect on the maximum stress (less than 1.6%).

Discussion

The muscle forces for an upright body position were estimated for the intact spine as well as after vertebroplasty and kyphoplasty and their effects on intradiscal pressure and stresses in the endplates were determined.

Several simplifications and assumptions were necessary in this study. Intact vertebral endplates were assumed in the fractured vertebra. A fractured endplate would reduce intradiscal pressure and lead to different stress distribution in the vertebral endplate. For the intact model, the loading case standing was supposed to be characterized by a fixed orientation of the L1 vertebra, and only a change of the shape within the lumbar spine was allowed [19, 21, 32]. This assumption has not been proven, but small deviations of this orientation have only a minor effect on spinal loads. The compensation of the upper body CoG shift in the vertebroplasty and kyphoplasty models was assumed to occur solely in the hips, the lumbar or the thoracic spine although the compensation methods are probably combined. Only one wedge angle each at level L3 was studied for vertebroplasty and kyphoplasty but there is a great variety in clinical situations. The height restoration during the kyphoplasty procedure depends strongly on the duration between fracture and treatment. When fresh fractures are treated, better height restoration can be achieved [11].

A wedge-shaped fracture of a vertebral body increases the flexion bending moment due to the upper body weight and thus a higher muscle force in the erector spinae is required to balance the spine. The flexion bending moment increases with the wedge angle of the vertebra. The force increase in the erector spinae due to a vertebral body fracture can be reduced by compensation of the upper body shift. Where the compensation occurs has only a minor effect on the muscle force.

For the vertebroplasty model, a rotation of 7.7° in the hip joints is sufficient to bring the upper body CoG back to the position of the intact spine. For compensation in the thoracic and in the lumbar spine, a rotation of 12° is required. Thus compensation mainly in the hip joints is more likely than compensation solely in the spine. Compensation in the lumbar spine causes a maximum force in the anterior longitudinal ligament of 145 N while in the other cases this force is less than 35 N.

The calculated pressure for the intact spine (0.52 MPa) agrees very well with the value measured in a volunteer (0.5 MPa) for relaxed standing [30]. A higher force in the erector spinae results in a higher spinal load and a higher intradiscal pressure. The erector spinae is a long muscle and thus its force affects intradiscal pressure not only at the levels adjacent to the fractured vertebra but also in the whole region. The calculated pressure in the uncompensated vertebroplasty model (0.81 MPa) is very similar to the value measured in a volunteer (0.83 MPa) for sitting with maximum flexion of the upper body [30]. Compensation of the upper body shift reduces not only the force in the erector spinae but also the pressure in the discs. Compared to the intact model, the horizontal distance of the CoG of the upper body weight is increased after compensation in the hip or thoracic spine. For compensation in the lumbar spine, additional muscle force is required to deform the lumbar spine. Therefore, muscle force and intradiscal pressures are higher for all three compensation methods studied than for the intact lumbar spine.

After augmentation of an intact or fractured vertebral body, intradiscal pressure in both adjacent discs is increased by about 2.4%. Applying an axial compression load Polikeit et al. [17] predicted a pressure increase of 16% above the treated level and 13% below the treated level, and Baroud et al. [1] reported an increase of 19% above the treated level. The differences compared to our results are presumably due to different modelling of the intervertebral discs and different loads.

The maximum von Mises stress in the endplates of the unfractured vertebrae are increased after kyphoplasty and vertebroplasty. This is not limited to the adjacent vertebra but is the case in all lumbar vertebrae. The effect of cement augmentation is much smaller. Compensation mostly reduces the maximum values, however, they are nearly always higher than for the intact spine. Upper body shift compensation in the lumbar spine even increases at three levels the maximum stress to values above those for the vertebroplasty model. In that case, intersegmental rotation is strongly increased. The predicted higher maximum stresses in the endplates of all vertebrae increase the risk of a new fracture in any lumbar vertebrae. Only relative stress values are presented in this paper since the absolute values depend on the assumptions made. Our intact model was validated using experimentally determined data for intersegmental rotation and intradiscal pressure. No experimental stress values exists for enabling validation.

Using stress profilometry, Pollintine et al. [18] found for cadaveric lumbar motion segments with a severely degenerated disc a noticeable load shift from the anterior column to the posterior region. There specimens were subjected to 2 kN of compressive loading to simulate erect posture. They discussed that the anterior stress shielding may cause bone loss. This, in turn, may be the reason for a wedge-shaped vertebral body fracture during flexion where high loads are predicted on the anterior side of the vertebral body. In contrast to the work of Pollintine et al. we assumed non-degenerated discs in our model. A wedge-shaped vertebral body fracture reduces the force on the neural arch. Further work is required to determine the effect of a degenerated disc in combination with a vertebral fracture.

Correction of the kyphotic deformity by kyphoplasty also reduces the upper body shift and thus the erector spinae force and the intradiscal pressure. In fact, from the mechanical point of view, height restoration of a vertebral body with a wedge-shaped fracture is advantageous, especially for those patients with severe osteoporosis. However, there is no strong clinical evidence yet to indicate that fracture reduction with kyphoplasty is any more successful than with vertebroplasty. The full

benefits of kyphoplasty reported in this paper are limited to the case, that nearly full fracture reduction is achieved.

Osteoporosis is a systemic disease and more than just one vertebra is involved. Therefore, the strength of at least several vertebrae is reduced. It is still a bone of contention as to what percentage of adjacent vertebral body fractures is due to natural progression and what percentage is due to cement augmentation.

Davis et al. [4] found that in women, a prevalent vertebral fracture increases the risk of incidence fractures anywhere in the spine by 30%. However, if the prevalence fracture was in L2–L5 the odd ratio increased from 1.3 to 5.7 compared to women with no prevalent fracture. Their results suggest that the increased fracture risk of women with prevalent fractures extends beyond the nearby vertebrae, can affect vertebrae both above and below the prevalent fracture. The authors discuss three reasons as to why a prevalent fracture increases the risk of incident fracture. First, the prevalent fracture is an indicator of impaired bone strength, second, the loading is altered and third the prevalence fractures are due to other risk factors for fracture, such as falling. Our results support the second reason since an increased loading after a wedge-shaped vertebral body fracture was observed in our study.

Another risk factor of new fractures of adjacent vertebral bodies is cement leakage into the disc. Lin et al. [13] studied 38 patients in whom 96 vertebroplasties were performed. There were 109 discs separating newly treated vertebral bodies from adjacent vertebra that had no previous fracture or treatment. Ten from 18 patients with cement leakage into the disc developed new fractures, but only 4 from 20 patients without cement leakage. From the vertebral bodies adjacent to a disc with cement leakage 58% fractured while only 12% vertebral body fractures were found adjacent to a disc without cement leakage.

Kim et al. [10] evaluated the risk factors of new compression fractures in adjacent vertebrae after vertebroplasty. They studied 106 patients with 212 vertebroplasties and evaluated five vertebrae superior and inferior to the treated vertebra. They found that shorter distance from the treated vertebrae, thoracolumbar junction, and a greater degree of height restoration of the cemented vertebrae may increase the fracture risk of vertebrae adjacent to treated vertebrae. The fact that fractures in vertebrae immediate to the treated one were not the only ones fractured shows that it is not necessarily a local effect. The latter risk factor is not in agreement with the reduced fracture risk due to height restoration predicted in our study.

Jenson and Dion [9] studied 109 patients with 174 fractures retrospectively and found no statistical difference in the rate of adjacent level fractures between patients who returned with new fractures following vertebroplasty and a control group consisting of patients who presented with multiple fractures of the same acuteness. Existing fractures are strong independent predictors of the risk of future vertebral fractures (Davis et al.). Thus the vertebrae adjacent to the site of cement injection are at no higher risk of fracture than any other vertebrae.

Conclusions

A wedge-shaped fracture of a vertebral body shifts the CoG of the upper body anteriorly and thus increases the force in erector spinae, intradiscal pressure and the endplate stresses. Compensation of the shift leads to a smaller muscle force and increase in spinal load. Injecting of PMMA in a vertebra increases the pressure in the adjacent discs and the maximum von Mises stress in the vertebral endplate only slightly. Even with shift compensation, the increases of intradiscal pressure and maximum von Mises stress in the endplates are much higher due to the elevated force in the erector spinae than due to cement augmentation. Fractures in a vertebra adjacent to an augmented one are probably not caused by the higher vertebral stiffness but by the increased load. Deformity correction reduces the increase of spinal load due to wedge-shaped fracture. Thus, our results suggest that for patients with osteoporotic vertebrae, treatments with kyphotic angle restoration are more advantageous than those without the treatment.

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