Analysis of the Physiological Load on Lumbar Vertebrae in Patients with Osteoporosis: A Finite-element Study

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Abstract

Purpose: This study aims to investigate the difference in physiological loading on the spine in three different motions (flexion-extension, lateral bending, and axial rotation) between osteoporotic and normal spines, using finite element modelling.

Methods: A three-dimensional finite element (FE) model centered on the lumbar spine was constructed. We applied two different material properties of osteoporotic and normal spines. For the FE analysis, three loading conditions (flexion-extension, lateral bending, and axial rotation) were applied.

Results: The load was higher on the nucleus pulposus at all vertebral levels in all movements, in the osteoporosis group than in the normal group. On the annulus fibrosus, the load increased at the level of L3-L4, L4-L5, and L5-S in the flexion-extension group and at L4-L5 and L5-S levels in the lateral bending group. The values of flexion-extension and lateral bending increased in two motions in the L4 and L5 cortical bones and in axial rotation at the level of L5. Additionally, the load increased in the lower endplate of L5-S and L4-L5 in all movements, especially lateral bending. Even in the group with no increase, there was a part that received increased load locally for each element in the three-dimensional reconstructed view of the pressure distribution in color.

Conclusion: The load on the lumbar region in the three loading conditions, was greater in most components of osteoporotic vertebrae than in normal vertebrae and the value was highest in the nucleus pulposus. Considering the increase in the measured load and the local increase in the pressure distribution, we believe that these results can contribute to explaining discogenic pain and degeneration.

Introduction

Osteoporosis is a worldwide health problem of considerable magnitude. It is the most common cause of fractures and is estimated to affect 1.5 million individuals each year ¹. Moreover, the risk of fractures due to trauma increases in patients with preexisting osteoporosis ². Osteoporotic fractures are classified as vertebral or non-vertebral and occur most commonly in the hip, wrist, and humerus ³. In Europe, according to the European Vertebral Osteoporosis Study (EVOS), the prevalence of osteoporosis is 12.2% among males and 12% in those aged between 50 and 79 years ⁴. The annual incidence is 1%, 2%, and 3% in women aged 65, 75, and 85 years, respectively. In males over 50 years of age, the prevalence ranges between 5.7 and 6.8/1,000 person/years, which is equivalent to approximately half of that seen in women ⁵. Osteoporosis and poor bone health, similar to other chronic diseases, are increasingly becoming a burden on society.

Vertebral compression fractures are the most common type of osteoporotic fracture ⁶. These may cause low back pain and limitation of daily life owing to pain, which can become chronic ⁷. Management of chronic pain in patients with osteoporosis involves a combination of pharmacological and nonpharmacological therapies and exercises to improve axial stability ⁸. However, since it is difficult to

measure the difference in pressure within spinal structures, experimental studies on the difference in pressure distribution between normal and osteoporotic vertebrae have rarely been conducted.

We believe that the physical properties of the osteoporotic spine differ from those of the normal spine. As a result, the vertebral load is expected to be higher in the osteoporotic spine. This study aims to investigate the difference in physiological load on the spine with three different motions between osteoporotic and normal spines, using finite element modelling. To our knowledge, this is the first study evaluating this research hypothesis.

Methods

A three-dimensional (3D) finite element (FE) analysis was carried out to investigate the effects of various load modes (flexion-extension, lateral bending, and axial rotation) on the lumbar spine and disc, in normal and osteoporotic patients. The distribution of the calculated von Mises stress was observed by applying loads to a 3D finite element model, including the lumbar vertebrae and disc. This work was supported by the Biomedical Research Institute grant, Kyungpook National University Hospital (2021).

Development of the FE model

A 3D FE model centered on the lumbar spine was constructed. It comprised the sacrum, L1 to L5 lumbar vertebrae (including the cortical and cancellous bones and posterior element), intervertebral discs (including nucleus pulposus and annulus fibrosus), endplates, and facet joints, as shown in Figure 1. The posterior elements consisted of the pedicles, lamina, facets (articular process), and transverse and spinous processes. The end plate was a bilayer of cartilage and bone that separated the intervertebral discs from the adjacent vertebrae. The 3D FE model was completed by converting the surface model into a solid model using CT data. Model conversion was performed using the 3D computer-aided design (CAD) softwares, CATIA (Dassault Systèmes, Vélizy-Villacoublay, France) and ANSYS SpaceClaim, (SpaceClaim Corporation, Concord, MA, USA).

Mesh and material properties for the FE model

The mesh for the FE analysis was created using the Static Structural module of the ANSYS Workbench. The element size was determined through a sensitivity analysis of the mesh. For FE analysis, material properties such as the elastic modulus and Poisson's ratio of the components, are required⁹. These material properties differ in normal and osteoporotic patients; patients with osteoporosis have lower bone density than normal individuals. Therefore, the elastic modulus of components related to bone, such as the cortical, cancellous, and posterior parts of the vertebra, is small. In contrast, the modulus of elasticity of intervertebral discs is relatively larger in osteoporotic patients than in normal individuals. Information on the mesh and material properties for the FE model is summarized in Table 1^{10–12}.

Table 1
Information of mesh and material properties for the finite element model

Item	Number of Nodes	Number of Elements	Elastic Modulus		Poisson's Ratio V		Reference
			E (MPa)				
			Normal	Osteoporosis	Normal	Osteoporosis	
Cortical bone	69,667	37,138	12,000	8,040	0.3	0.3	11,12
Cancellous bone	71,381	47,169	200	34	0.25	0.25	11,12
Posterior bone	37,963	20,990	3,500	2,345	0.25	0.25	11,12
Endplate	30,138	13,503	1,000	670	0.3	0.3	10,11
Nucleus pulposus	346,396	239,611	1	9	0.49	0.4	10,11
Annulus fiber	358,484	239,295	4.2	5	0.45	0.45	10,11
Facet joint	1,842	474	11	11	0.4		12
MPa, megapascal;							

Loading and boundary conditions

For the FE analysis, three loading conditions (flexion-extension, lateral bending, and axial rotation) were applied, as shown in Figure 2. A moment of 400 N·m was applied to the human body structure. The total degrees of freedom of the sacrum were fixed, and bonding contact conditions were applied to each component of the human body so that they did not separate from each other when a load was applied.

Results

Von Mises stress in the spine FE Model

The von Mises stress was compared with the average of each component volume. Tables 2 to 4 show the von Mises stress results for each loading mode.

Table 2
von-Mises stress results for Flexion-Extension loading mode.

Component	Lumbar level	Osteoporosis (A) (MPa)	Normal (B) (MPa)	Loading ratio (A-B)/B×100 (%)
Cortical bone	L1	25.126	28.122	-10.65
	L2	53.361	70.227	-24.02
	L3	43.054	52.126	-17.40
	L4	57.693	55.173	4.57*
	L5	43.967	30.076	46.19*
Cancellous bone	L1	0.51006	1.2454	-59.04
	L2	0.64338	2.4965	-74.23
	L3	0.68258	2.2162	-69.20
	L4	1.0499	2.3183	-54.71
	L5	1.1709	1.6815	-30.37
Posterior bone	L1	5.3673	13.053	-58.88
	L2	7.6343	16.807	-54.58
	L3	10.621	17.928	-40.76
	L4	11.871	13.915	-14.69
	L5	10.534	10.699	-1.54
Lower endplate	L1-L2	56.732	82.265	-31.04
	L2-L3	47.543	70.456	-32.52
	L3-L4	33.017	48.089	-31.34
	L4-L5	24.117	26.97	-10.58
	L5-S	8.424	5.8443	44.14*
Upper endplate	L1-L2	44.762	64.95	-31.08
	L2-L3	67.358	100.08	-32.70
	L3-L4	47.912	69.273	-30.84
	L4-L5	46.778	63.812	-26.69
	L5-S	26.971	30.933	-12.81

Component	Lumbar level	Osteoporosis (A) (MPa)	Normal (B) (MPa)	Loading ratio (A-B)/B×100 (%)
Annulus fiber	L1-L2	1.5629	2.0654	-24.33
	L2-L3	2.6575	3.4548	-23.08
	L3-L4	3.2907	3.0178	9.04*
	L4-L5	5.7342	5.3602	6.98*
	L5-S	6.5444	5.818	12.49*
Nucleus pulposus	L1-L2	2.1013	0.46321	353.64*
	L2-L3	3.2781	1.8385	78.3*
	L3-L4	3.3553	1.8947	77.09*
	L4-L5	4.2502	1.3132	223.65*
	L5-S	4.8262	1.5877	203.97*
MPa, megapascal; *, percentage of increased load in osteoporosis than normal;				

Table 3
von-Mises stress results for Lateral bending loading mode.

Component	Lumbar level	Osteoporosis (A) (MPa)	Normal (B) (MPa)	Loading ratio (A-B)/B*100 (%)
Cortical bone	L1	13.497	16.516	-18.28
	L2	32.68	45.26	-27.79
	L3	37.049	41.368	-10.44
	L4	52.804	47.511	11.14*
	L5	46.602	31.986	45.69*
Cancellous bone	L1	0.12077	0.39291	-69.26
	L2	0.29689	0.90154	-67.07
	L3	0.6554	1.4151	-53.69
	L4	0.29689	1.8355	-83.83
	L5	0.12077	2.1061	-94.27
Posterior bone	L1	3.418	8.6089	-60.30
	L2	4.2622	8.6113	-50.50
	L3	6.8846	11.261	-38.86
	L4	9.1897	10.523	-12.67
	L5	15.874	18.713	-15.17
Lower endplate	L1-L2	40.946	64.309	-36.33
	L2-L3	38.612	61.885	-37.61
	L3-L4	25.25	37.471	-32.61
	L4-L5	19.487	18.555	5.02*
	L5-S	7.6198	6.0725	25.48*
Upper endplate	L1-L2	32.16	49.854	-35.49
	L2-L3	52.787	83.705	-36.94
	L3-L4	39.689	60.355	-34.24
	L4-L5	37.619	49.207	-23.55
	L5-S	19.313	20.299	-4.86
Annulus fiber	L1-L2	1.7252	3.2563	-47.02

Component	Lumbar level	Osteoporosis (A) (MPa)	Normal (B) (MPa)	Loading ratio (A-B)/B×100 (%)
	L2-L3	2.8048	4.6763	-40.02
	L3-L4	4.4374	5.293	-16.16
	L4-L5	5.5855	5.5839	0.03*
	L5-S	5.7893	5.6254	2.91*
Nucleus pulposus	L1-L2	2.4159	0.69101	249.62*
	L2-L3	3.9118	0.9813	298.63*
	L3-L4	5.2183	1.1694	346.24*
	L4-L5	4.3405	1.4543	198.46*
	L5-S	4.5578	1.3158	246.39*
MPa, megapascal; *, percentage of increased load in osteoporosis than normal;				

Table 4
von-Mises stress results for Axial rotation loading mode.

Component	Lumbar level	Osteoporosis (A) (MPa)	Normal (B) (MPa)	Loading ratio (A-B)/B×100 (%)
Cortical bone	L1	1.7847	2.9347	-39.19
	L2	5.559	9.1105	-38.98
	L3	3.6444	6.1652	-40.89
	L4	4.8083	8.3163	-42.18
	L5	43.408	41.068	5.7*
Cancellous bone	L1	0.0151	0.0633	-76.15
	L2	0.0306	0.14743	-79.24
	L3	0.0313	0.15748	-80.12
	L4	0.0235	0.11987	-80.40
	L5	0.61867	1.598	-61.28
Posterior bone	L1	0.11104	0.28003	-60.35
	L2	0.31113	0.59648	-47.84
	L3	0.64636	1.3479	-52.05
	L4	0.94167	1.9366	-51.38
	L5	38.26	47.385	-19.26
Lower endplate	L1-L2	9.6145	16.477	-41.65
	L2-L3	6.1934	10.881	-43.08
	L3-L4	5.9779	10.619	-43.71
	L4-L5	7.0101	9.6956	-27.70
	L5-S	7.5692	5.3671	41.03*
Upper endplate	L1-L2	6.7984	11.463	-40.69
	L2-L3	8.3617	14.076	-40.60
	L3-L4	4.2539	7.4382	-42.81
	L4-L5	6.0596	10.761	-43.69

Component	Lumbar level	Osteoporosis (A) (MPa)	Normal (B) (MPa)	Loading ratio (A-B)/B*100 (%)
Annulus fiber	L5-S	14.466	16.651	-13.12
	L1-L2	0.0386	0.0688	-43.90
	L2-L3	0.12801	0.26926	-52.46
	L3-L4	0.14739	0.2947	-49.99
	L4-L5	0.26848	0.43696	-38.56
	L5-S	7.301	8.3341	-12.40
Nucleus pulposus	L1-L2	0.0303	0.0152	99.34*
	L2-L3	0.10799	0.055	96.35*
	L3-L4	0.12821	0.058	121.05*
	L4-L5	0.30552	0.0769	297.3*
	L5-S	7.6572	1.587	382.5*
MPa, megapascal; *, percentage of increased load in osteoporosis than normal;				

We compared the load on each component at each level of the lumbar spine between the osteoporosis and normal groups. The ratio of the load difference, expressed as a percentage, was calculated using the formula $(A-B)/B \times 100$ (%), where A and B represent the osteoporotic and normal groups, respectively. A positive value denotes that the osteoporosis group takes more load than the normal group.

Comparing the osteoporosis and normal groups in the flexion-extension action group, the values of L4 and L5 cortical bones as per the above formula were 4.57% and 46.19%, respectively, indicating that the load increased by this value in osteoporosis. The cancellous and posterior bones and the upper endplate, did not differ between the two groups. In the lower endplate of L5-S, the load increased by 44.14% in osteoporosis. In addition, L3-L4, L4-L5, and L5-S annulus fibers in the osteoporosis group had loads higher by 9.04%, 6.98%, and 12.49%, respectively. At all levels from L1-L2 to L5-S, the loads on the nucleus pulposus increased by 353.64%, 78.3%, 77.09%, 223.65%, and 203.97%, respectively.

In the lateral bending motion group, the load in the osteoporosis group increased to 11.14% and 45.69% in the cortical bone of L4 and L5, respectively, and to 5.02% and 25.48% in the lower endplate of the L4-L5 and L5-S, respectively. In addition, the loads on L4-L5 and L5-S annulus fibers increased slightly by 0.03% and 2.91%, respectively, and across all levels, the load on the nucleus pulposus increased by 249.62%, 298.63%, 346.24%, 198.46%, and 246.39%, in the osteoporosis group.

Finally, in the axial rotation group, the load on the cortical bone of L5 in the osteoporosis group increased by 5.7% and that on the lower endplate of L5-S increased by 41.03%. As in the other motions, the load in the nucleus pulposus at all lumbar levels, increased by 99.34%, 96.35%, 121.05%, 297.3%, and 382.5%, respectively. There were no differences between the two groups with respect to the annulus fibrosus, including the cancellous and posterior bones and the upper endplate.

All three motions, flexion-extension, lateral bending and axial rotation, had the largest absolute values in the nucleus pulposus at all lumbar spine levels, suggesting that it bore a large load in osteoporosis. In particular, the values were large in the flexion-extension and lateral bending motions and relatively small during axial rotation.

We also reconstructed the above results in 3D and expressed the difference in load distribution of the entire part including the surface, in color. Figure 3 shows an analysis of the cortical bone. Looking at L4 and L5 in the above results, which show that more load is received in osteoporosis, it was confirmed that the value of the load corresponding to red at a specific part of the interface, was high. In the results of the table above (even from L1 to L3, which had a positive value), there was a specific part in which the load corresponding to red was increased. Figure 4 shows the load distribution for the intervertebral discs, including the annulus fibrosus and nucleus pulposus. Regarding the cortical bone, it can be seen from the image that there is a partially increased part even in the group where the calculated load value does not appear to have increased.

Discussion

In this study, FE analysis was used to compare the von Mises stresses on the lumbar spine and intervertebral discs when various load-modes were applied to normal and osteoporotic spines. The cortical bone had the greatest von Mises stress, that is, the load was found to be concentrated on the cortical bone that supports the body structure. In particular, the largest von Mises stress occurs at L4 and L5, and it can be seen that in patients with osteoporosis, the stress is greater than that in normal persons at the corresponding positions (L4 and L5). In the nucleus pulposus, it was confirmed that patients with osteoporosis had 77.09-382.50% greater von Mises stress than those without. However, because the results shown in Tables 2 to 4 are based on the total value for each part, there is a limitation in that the load increase in specific parts cannot be reflected, as shown in figures 3 and 4. In other words, even if it has a positive value, it can be compensated for by a sufficiently negative value, meaning that more load is applied if a specific part is coordinated. Therefore, the table value and 3D load distribution in color should be simultaneously compared, and the fact that a positive value does not indicate less load should not be overlooked. As shown in Figures 3 and 4, the fact that the osteoporosis group had a higher load on the surface bordering other adjacent sites may help explain the mechanism by which the following phenomena occur. First, it will be helpful to explain the mechanisms by which (a) osteophyte develops in the spine secondary to degeneration, and (b) intervertebral disc degeneration results in discogenic pain ¹³⁻¹⁵. In other words, in osteoporotic patients, the load on the nucleus pulposus is more concentrated than that in normal individuals, which can accelerate disc degeneration ^{16,17}.

Furthermore, several studies have shown that chronic back pain is caused by spinal deformity or kyphosis in patients with osteoporosis; furthermore, chronic low back pain tends to improve with pharmacological treatment of osteoporosis. According to our experimental model, this result can be explained by the difference in stress applied to each part in osteoporotic patients. These results further suggest a potential reduction in the incidence of vertebral fractures after proper treatment for osteoporosis in such patients. According to previous studies, pharmacological treatment is effective in preventing osteoporotic fractures¹⁸. Based on our research, we believe that the pharmacological treatment of osteoporosis will help prevent fractures by affecting the physical properties of each element of the spine analyzed above, leading to a reduction in the load on each element.

This study has several limitations. First, the incidence of osteoporotic vertebral fractures is highest in the lower thoracic (T11 and T12) and upper lumbar (L1) vertebrae⁷. However, this study was conducted only on the lumbar spine, which, while advantageous for controlling variables, excludes the thoracic spine. Second, our FE model did not include tendons, nerves, ligaments, and muscles, and did not reflect the variability of these structures between the two groups and for each motion. However, the effect of the structures was minimized through comparative analysis, with the results obtained by including the structures above¹⁹. In addition, the differences in intervertebral disc height or physical properties were not reflected in the performance of each motion. Third, because this study is a model-based analysis, it is limited in that it does not reflect the actual clinical characteristics and risk factors of osteoporosis. Although it was based on the physical properties of each component in osteoporosis, as presented in Table 1, it is difficult to accurately represent the condition of the individual spine in clinical practice. As mentioned above, structural differences such as bony spur or disc degeneration, are often accelerated when osteoporosis is already present, but it is difficult to fully reflect these factors in a single model. In addition, it does not reflect the risk factors related to osteoporosis, such as age, low body weight, glucocorticoid therapy, current cigarette smoking, excessive alcohol consumption, previous fracture, and secondary osteoporosis^{20,21}.

Conclusion

In conclusion, the load on the lumbar region in the three motions-flexion-extension, lateral bending, and axial rotation-was greater in most components of osteoporotic vertebrae, and the load was highest in the nucleus pulposus. According to the three-dimensionally reconstructed pressure distribution diagram, even in areas where the load did not increase, these factors may help explain the discogenic pain or degeneration occurring in osteoporosis, via a local increase in pressure in some regions.

Declarations

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Author contributions

S.K., M.C., K.T.K. and J.M.H. planned the experiments. S.K. and M.C. performed processing of the model analysis. C.H.P. wrote original draft preparation. S.L., Y.S.M. and C.H.K. reviewed and edited the writing. G.H.J., D.H.K. and J.M.H. performed the data analysis. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Data availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

Figure 1

Results of analysis of loading on each vertebral level in flexion-extension.

Figure 2

Three loading conditions (flexion-extension, lateral bending, and axial rotation)

Figure 3

von-Mises Stress Results at cortical bone in three different motions (Unit: MPa).

Figure 4

(a): von Mises stress distribution on the intervertebral disc in flexion-extension loading mode. As a result of analysis in flexion-extension motion, the stress was concentrated in the annulus fibrosus of L3-L4, L4-L5 and L5-S1, and in the nucleus of whole level of lumbar (Unit: MPa).

(b): von Mises stress distribution on the intervertebral disc in lateral bending loading mode. As a result of analysis in lateral bending motion, the stress was concentrated in the annulus fibrosus of L4-L5 and L5-S, and in the nucleus of whole level of lumbar (Unit: MPa).

(c): von Mises stress distribution on the intervertebral disc in axial rotation loading mode. As a result of analysis in axial motion, the stress was mainly concentrated in the nucleus of whole level of lumbar (Unit: MPa).