# Finite element method based stress analysis of zone I and zone II sacral fractures

## Birinci ve ikinci bölge sakrum kırıklarının sonlu eleman metoduna dayalı gerilme analizi

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*AMAÇ*

Sakrum kırıkları direkt ve indirekt travmalardan sonra görülmektedir. Direkt travmalar, sakral bölgenin künt travmaları veya ateşli silah yaralanmaları şeklinde olup nadiren görülürler. Daha sık görülen indirekt travmalar ise motorlu araç kazaları ve belirli yükseklikten düşme sonrasında kemiğin dik ekseninde olan kayma hasarı sonrasında oluşurlar.

*GEREÇ VE YÖNTEM*

Bir kadavranın sakrum kemiği sonlu eleman programı yardımıyla 1 mm aralarla üç boyutlu olarak modellendi. Sol sakroiliyak eklem, 75 kg bir adamın 5 m yükseklikten bir bacağının üstüne düşmesi şeklinde modellendi. Sakruma intervertebral disk ve her iki faset yüzeylerinden 10 kN'luk ani yükleme uygulandı. Von Mises eşdeğeri gerilme dağılımı saptandı.

*BULGULAR*

Sakrum kanadında (430 MPa), S1 pedikülü (225 MPa) ve laminasında (35 MPa) Von Mises gerilme dağılımları hesaplandı. S1 foramenindeki gerilme değerleri; ön dışyanda 200 MPa, arka içyanda 130 MPa, ön iç yanda 105 MPa ve arka dışyanda 55 MPa idi. Eksene dik kayma hasarının etkisi ile gerilme dağılımının sakrum kanadında ve S1 pedikülünde (bölge 1) ve S1 foramen çevresindeki foramenin ön dış yanında yoğunlaştığı görüldü.

*SONUÇ*

Sakrumun birinci bölge kırıklarının daha sık görülmesi ve nörolojik sekel sıklığının daha az olması gerilmelerin sakrumun kanadında yoğunlaşması ile açıklanabilir. İkinci bölge kırıklarının, sakrum kanadında ve S1 pedikülündeki gerilmelerin tetiklenmesi ile S1 foramenninin ön dış yanına geçmesi sonucunda oluştuğu yorumunda bulunulabilir.

*Anahtar Sözcükler:* Sonlu eleman metodu; sakrum; biyomekanik çalışma; omurga hasarı.

*BACKGROUND*

Sacral bone fractures after direct traumas such as gunshot wounds and blunt sacral traumas are rarely, whereas those occurring after indirect traumas with vertical shear mechanisms ( car accidents or falls) are more frequently seen.

*METHODS*

A cadaver sacrum was modelled 3-dimensionally using finite element software. Left sacroiliac joint was modeled to simulate a 75- kg man falling on one leg from a height of 5 meters. An impact load of 10 kN was transferred to the sacrum via intervertebral disc surface and two facets. Von Mises equivalent stress distribution was estimated.

*RESULTS*

Von Mises stress distribution was calculated for sacral ala (430 MPa), S1 pedicle (225 MPa), and S1 lamina (35 MPa). Stress values were 200 Mpa, 130 Mpa, 105 Mpa, and 55 MPa on ventrolateral, dorsomedial, ventromedial and dorsolateral sides of S1 foramen respectively. Vertical shear injury caused stress distribution to concentrate at sacral ala and S1 pedicle (zone I). Local stress distribution around S1 foramen is concentrated ventrolaterally

CONCLUSION

High incidence of zone I sacral fractures and low incidence of neurological deficits could be explained by concentration of stress at sacral ala. Zone II fractures might be due to by transfer of triggered stresses from sacral ala and S1 pedicle to ventrolateral side of S1 foramen.

*Key Words:* Finite element method; sacrum; biomechanical study; spine injury.

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Indirect sacral fractures can occur under the effect of a vertical shear injury such as in falls from a certain height. The loads are transferred to the sacrum through the pelvis and/or the lumbar spine and neurological deficit is observed when the injury is accompanied by pelvic trauma.[1,2]

Type of the sacral fracture has been classified with anatomical regions of the bone.[3] Zone I fractures involve sacral ala but not the sacral foramina or the sacral canal. Zone II fractures involve only sacral foramina. Zone III-A (vertical fracture) and zone III-B (transverse fracture) fractures, on the other hand, involve the sacral foramina and the sacral canal.

In the physiologic posture, upper body weight is transmitted through the sacrum body and two articular facets to the sacroiliac surfaces and the force vectors of axial loads from the spine are located ventral to the sacroiliac joint. This vector orientation causes a ventral bending moment of the sacrum at the level of the sacroiliac joint. The sacrospinous and sacrotuberous ligaments work through a long moment arm by which they are able to resist sacral bending thereby enabling the maintenance of the lordotic lumbosacral posture.[4,5]

The internal architecture of the sacrum is such that strong trabeculae traverse S1-S2 in the horizontal plane, and intersect with each other on the anterior surface of the interforaminal area (zone II). This area could be regarded as the condensation area, which is the thickest and the most compact part of the bone. It can be predicted that load is transmitted through the upper sacrum, and then through the sacroiliac surfaces into the hips.[6]

In this study, stress distribution on the sacrum due to a vertical shear injury was examined by the finite element (FE) analysis for a specific case of a fall from a certain height. This information is valuable because it improves understanding of why particular fracture patterns are observed and why certain fracture patterns are associated with neurological injury while others are not.

## MATERIALS AND METHODS

### *Cadaver Sacrum Model*

The sacrum of a man who died of cerebral ischemia one year ago at the age of 56 was extracted for the morphologic data of the study. The bone was resected from the pelvis, and was cleaned from all adhering soft tissues, the periostal membrane and ligaments. Anteroposterior and lateral radiological images of the bone showed no traumatic pathology.

The bone was cut at the median sacral crest (mid-sagittal plane) to identify the cortical and trabecular regions. Using calipers, the cortical region thickness was measured at the ventral and dorsal surfaces of the sacrum and also the anterior and posterior sides of the sacral canal at all sacral levels. The average cortical thickness was assumed to be 2 mm at the ventral and dorsal surfaces. Cortical thickness along the sacral canal was approximately 1 mm at all levels.

### *The Finite Element Model*

Because of the complex structure of the sacrum, its solid model was obtained using surface modelling techniques. The geometry of the sacrum was transferred to a computer through a three-dimensional digitizer (Cyclone 3D digitizer, Renishaw, Gloucestershire, UK). The ventral and the dorsal surfaces of the sacrum were scanned along the surface with a stepsize of 1 mm for discretization of the continuous three-dimensional body. This procedure was done to form the necessary pattern of nodes to follow the actual curves and surfaces to be used in the numerical stress analysis. The raw data obtained from the digitizer was transferred to FE software (Catia V421-R1, Dassault Systemes&IBM, New York, NY). Two separate surface models were combined with connection surfaces to form a definite volume, and the result was defined as a solid model for the sacrum.

In the solid model, the cortical region was assumed as 2 mm inwards from the outer surface of the sacrum and 1 mm inwards along the sacral canal, as it was observed from the mid-sagittal plane of the cadaver model, and the rest of the bone was modelled as trabecular. The rudimantary disc spaces and the sacral canal in the sacrum were constructed by referencing the mid-sagittal plane of the cadaver model, and were assumed to be empty regions.

The material properties of the cortical and trabecular parts of the bone, which were obtained from the literature, are provided in Table 1.[7,8] The cortical bone was assumed to be linear anisotropic, whereas the trabecular bone was linear isotropic.

***Tablo 1:*** The material properties of the cortical and the trabecular part of the bone. [7,8]

| | Cortical bone | Trabecular bone |
|---|---|---|
| Young's Modulus (Longitudinal) | 8900 MPa | 1400 MPa |
| Young's Modulus (Tangential) | 4300 MPa | 1400 MPa |
| Young's Modulus (Radial) | 3800 MPa | 1400 MPa |
| Poisson Ratio | 0.3 | 0.3 |
| Density | 1300 kg/m$^3$ | 130 kg/m$^3$ |

The mesh model of the sacrum was composed of 116,233 four-noded isoparametric tetrahedrons and 26,313 nodes. The cortical part consisted of 85,560 elements and 19,369 nodes while the trabecular part consisted of 30,673 elements and 6,944 nodes.

The left sacroiliac articular surface of the solid model was fixed in all six degrees of freedom (translation in x, y, and z directions and the rotations about x, y, z axes).

The axial compressive impact load on the S1 intervertebral articular surface of the sacrum was modelled as 10 kN. This value was calculated for a man falling onto his left leg from a 5 m height. The impact time was experimentally determined. The experiments were carried on by allowing a sack of sand to fall from the same height. An accelerometer was placed on the sack and the velocity-versus-time plots were obtained using a spectrum analyzer (Type 2515 vibration analyzer, Type 4391 piezoelectric accelerometre, Brüel&Kjaer, Veenendaal, Denmark). The average impact damping duration was determined by repeating the experiments 5 times. The magnitude of the impact load has been calculated using the following equation obtained by the principle of conservation of momentum,

$$F = \frac{m\sqrt{2gh}}{\Delta t}$$

where m is the mass of the falling man (75 kg), g is gravitational acceleration (9.81 m/s$^2$), h is height in meters (5 m) and $\nabla$t is the duration of impact (0.075 s).

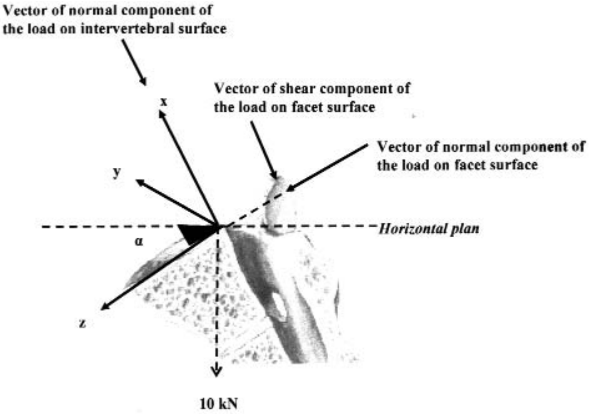

**Figure 1:** Schematic illustration of the vectorial components (normal and shear) of 10 kN gravitational vertical load on mid sagittal section of the sacrum. (α=sacrohorizontal angle: -45 degree on the horizontal plan)

Considering the sacrohorizontal angle of the sacrum, the 10 kN gravitational vertical load was distributed into vectorial components, which are normal and shear components (Figure 1). Normal component of the total load was applied on the intervertebral surface in –x direction and on the facets surface in +z direction with respect of their surface normals, whereas the shear component of the total load was distributed among the two facets surface in -x direction. With respect to –45 degrees of the sacrohorizontal angle about the horizontal plane, the magnitudes of these vectors were cal-

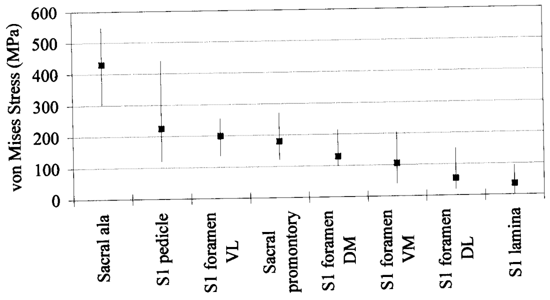

**Figure 2:** The minimum, maximum and median values of von Mises equivalent stress (MPa) after the application of 10kN axial compressive loading at the different anatomical localizations of the sacrum. (VL: ventral-lateral, DM: dorsal-medial, VM: ventral-medial, DL: dorsal-lateral)

culated as 7071 N compressive for the normal component, 7071 N for the total shear component. The angle between the z axis and the facet normal on the yz plane was assumed to be +90 degree, which implies 5000 N compressive load for each facet in +z direction. The loads applied on the aforementioned surfaces were arithmetically distributed over the nodes on respective surfaces in relevant directions. The numerical static analysis of the model was solved using ANSYS (Ansys 5.7, Ansys Inc., Canonsburg, PA). Under a load of 10kN, the von Mises equivalent stress distribution of the sacrum was calculated in comparison to the unloaded initial condition.

## RESULTS

The von Mises equivalent stress distribution on the sacrum for a 10 kN axial compressive load case is shown in Figure 2. The following stress values were observed at the sacral ala (min 300 MPa, max 550 MPa, median 430 MPa), the S1 pedicle (min 119 MPa, max 447 MPa, median 225 MPa), the S1 foramen ventral-lateral (VL) side (min 135 MPa, max 255 MPa, median 200 MPa), the sacral promontory (min 120 MPa, max 270 MPa, median 180 MPa), the S1 foramen dorsal-median (DM) side (min 100 MPa, max 214 MPa, median 130 MPa), the S1 foramen ventral-median (VM) side (min 40 MPa, max 204 MPa, median 105 MPa), the S1 foramen dorsal-lateral (DL) side (min 20 MPa, max 150 MPa, median 55 MPa), the S1 lamina (min 0 MPa, max 94 MPa, median 35 MPa). Based on the distribution, the highest and second highest von Mises values are observed at the sacral ala and the S1 pedicle. The minimum value was estimated at S1 lamina (Figures 3,4,5).

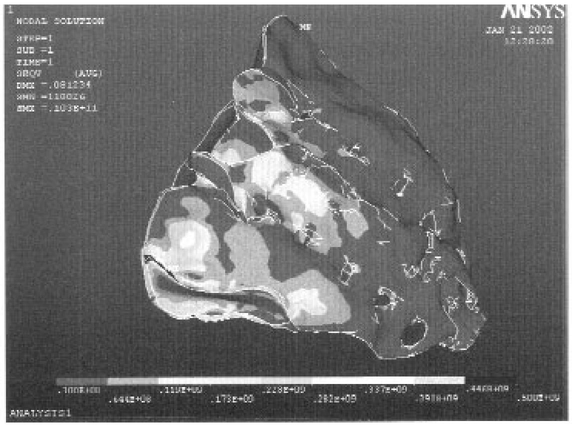

**Figure 4:** The von Mises equivalent stress distribution on the sacrum in a dorsal view was obtained after the application of a 10 kN axial compressive load. The color scale represents the scale of stress from the lowest at the left to the highest at the right.

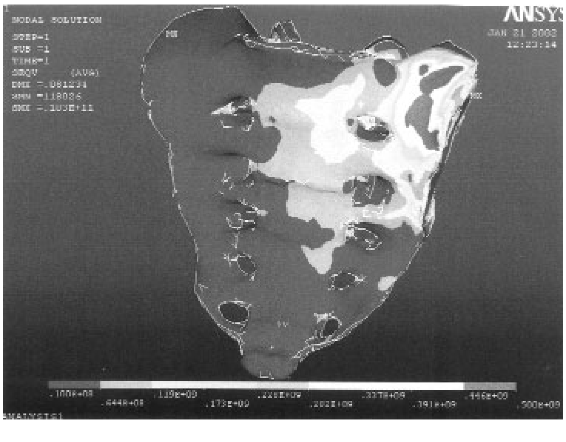

**Figure 3:** The von Mises equivalent stress distribution on the sacrum in a ventral view was obtained after the application of a 10 kN axial compressive load. The color scale represents the scale of stress from the lowest at the left to the highest at the right.

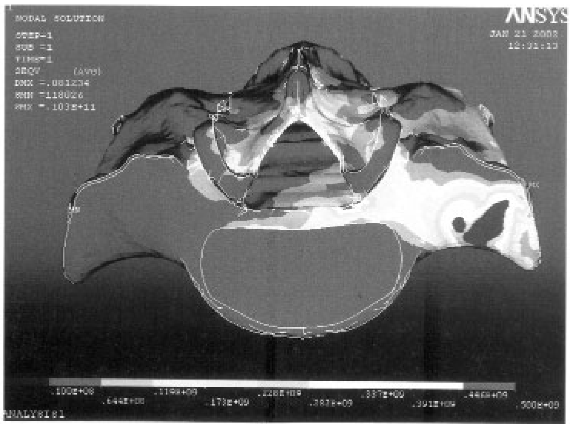

**Figure 5:** The von Mises equivalent stress distribution on the sacrum in a intervertebral view was obtained after the application of a 10 kN axial compressive load. The color scale represents the scale of stress from the lowest at the left to the highest at the right.

## DISCUSSION

The weight transmission through the sacrum has been studied in the literature.[4] Under the circumstances of the vertical shear injury such as falling from a certain height, the impact loads are transferred to the sacrum through the column femoris–pelvis-sacroiliac joint pathway. An equivalent load to this impact load accompanied by a ventral bending moment is transferred to the sacrum through L5 at the facets and the intervertebral disc surface. This ventral bending moment emerges because of two anatomical conditions: one of them is the physiological position of the sacrum, namely the sacrohorizontal angle and the global sacral kyphosis, and the other is the distance between the sacroiliac joint and the acetabular joint of column femoris in the lateral plane.

To simulate the aforementioned case in the FE model, the left sacroiliac joint, which is an amphiarthrodial joint that is assumed to have limited deformability, was fixed in all degrees of freedom and the impact load that remained in the axial plane was applied on the L5 interfaces using vector mechanics.

The center of gravity of a person is at the S1 level and is approximately 40 mm ventral to the lumbosacral joint.[9] The sacrum is fixed to the pelvis which is balanced with two femoral joints. Considering a man standing up, the moment on the femoral joints due to the eccentricity of the center of gravity are balanced with the moments generated by muscular structures. In case of impact loading, these muscles would be assumed to be passive elastic springs. Thus, the body would bend ventrally, since there would be very little or no moment generated by the muscles, or there is not an appropriate support as a boundary condition that would cause internal moments to appear to keep the body upright. The body is free to rotate about the femoral axis, thus there is no internal moment that acts on the sacrum. Considering the aforementioned complex behavior of the pelvic structure, no additional moment effects were taken into consideration for the analysis on the sacrum.[10]

The von Mises equivalent stress distribution under the aforementioned loading conditions demonstrates a peak near the fixed sacroiliac joint, and at the sacral ala, which gradually decreases from the sacroiliac joint to the S1 pedicle. The S1 pedicle connects the sacral ala to the S1 vertebra body above the neural foramen. Thus, the stress concentrations observed near the sacral ala and the S1 pedicle agree with the weight transmission study,[4] and can be classified as zone I according to the classification in the literature.[3] Focusing on the sacral foramina, the highest stress values are observed near the ventrolateral (VL) side of the S1 foramen, which is located at the lateral side of the S1 foramen in ventral view of the sacrum. Minimum values for the same region are interestingly demonstrated at the dorsolateral side of the S1 foramen, which is located at the lateral side of the S1 foramen on dorsal aspect of the sacrum.

The stress values of the VL and the DM sides were observed to exceed the stress values of the VM and the DL sides. Additionally, the ratio of VL to VM stress is 2. This variation agrees with internal architecture of the bone.[6] The authors showed in their study that there is a condensation zone between VM sides at the S1 foramina, which means that the VM sides of the S1 foramen are stronger than the VL sides. Moreover, the fracture line at the S1 foramen starts from the VL side, and this line could be assumed as the beginning of zone II. The median stress near the sacral promontory was observed to be 180 MPa. This zone was also been identified as a condensation zone.[6] The S1 lamina stress values were calculated as the lowest. This region is out of the load transfer path of sacrum, i.e, mainly the body of the sacrum and the two articular sides, and the calculated stress values are consistent with the speculated load transmission pathway of the sacrum.[4]

The stresses were mostly concentrated at the sacral ala and the S1 pedicle. This concentration may explain the high frequency of occurrence of zone I fractures observed clinically.[3,11,12] Around the S1 foramen, the highest stress values were observed at the VL side, and it may be concluded that for higher loading magnitudes, zone II fractures would be observed due to the transfer of stress from the sacral ala to the VL side of the S1 foramen.

### *The Limitations of the Study*

The reason why we did not observe zone III fractures in our study could be explained by the fact that the sacrospinous and sacrotuberous ligaments were neglected in our FE model. These two ligaments might prevent sacral bending by forming a moment arm. Further study is needed to assess the biomechanical contribution of these ligaments.

Since the strains that cause high stress values in cortical bone are insufficient for the trabecular bone to generate comparably high stress values stress values were much observedly much higher in cortical regions. Thus, the stress values for trabecular bone were not analyzed. Further investigation of the stress distribution on the sacrum using this model is limited by the isotropic trabecular bone material approximation.

Further studies on the stress distribution on the sacrum can focus on improving the material models that represent the trabecular and cortical bone, as well as taking account the deformability of ligaments and muscles. Modeling muscular structures could also enhance the load-transfer mechanisms. Nonlinear and viscoelastic material analysis can be run to investigate the variations in stress distribution and importance of these variations. Experimental analysis of stress distribution on sacrum would be another interesting topic to investigate and compare with the FE model results.

The results of this study suggest that stress concentrations after axial compressive loading such as a vertical shear injury to the sacrum are localized at the sacral ala. However, the lowest stress values were observed at the S1 lamina. Because of the tendency of the sacral ala to fracture, zone I fracture occurs much more frequently than the other types. If the stress magnitude is increased, the VL side of the S1 foramen will be affected, and zone II fracture would be observed. The low incidence of neurological deficits in sacral fractures could be explained by the concentration of stress at the sacral ala, which is located away from neural tissues.

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## REFERENCES

1. Byrnes DP, Russo GL, Ducker TB, et al. Sacrum fracture and neurologic damage. J Neurosurg 1977; 47: 459-462.
2. Gibbons KJ, Soloniuk DS, Razack N. Neurological injury and patterns of sacral fractures. J Neurosurg 1990;72: 889-893.
3. Denis F, Davis S, Comfort T. Sacral fractures; an important problem. Retrospective analysis of 236 cases. Clin Orthop 1988; 227: 67-81.
4. Pal GP. Weight transmission through the sacrum in man. J Anat 1989; 162: 9-12.
5. Panjabi MM, Oxland TR, Yamamoto I, et al. Mechanical behavior of the human lumbar and lumbosacral spine as shown by three-dimensional load-displacement curves. J Bone Joint Surg (Am) 1994; 76: 413-424.
6. Ebraheim N, Sabry FF, Nadim Y, et al. Internal architecture of the sacrum in the elderly. Spine 2000; 25: 292-297.
7. Hakim N, King A. A three dimensional finite element dynamic response analysis of a vertebra with experimental verification. J Biomech 1979; 12: 277-292.
8. White III AA, MM Panjabi. Biomechanics A to Z. In: White III AA, MM Panjabi, eds. Clinical Biomechanics of the Spine. 2nd ed. New York, Lippincott-Raven; 1990: 665-696.
9. Kong WZ, Goel VK, Gilbertson LG. Prediction of biomechanical parameters in the lumbar spine during static sagittal plane lifting. J Biomech Eng 1998; 120: 273-280.
10. Oxland TR, Crisco JJ 3rd, Panjabi MM, et al. The effect of injury on rotational coupling at the lumbosacral joint. A biomechanical investigation. Spine 1992; 17: 74-80.
11. David CA, Green BA. Injuries to the sacrum and pelvis. In: Wilkins RH, Rengachary SS, eds. Neurosurgery. 2nd ed. New York: McGraw-Hill; 1996: 3047-3053.
12. Schmidek HH, Smith DA, Kristiansen TK. Sacral fractures. Neurosurgery 1984; 15: 735-746.