DUAL-ENERGY X-RAY ABSORPTIOMETRY AS AN INDICATOR FOR FRAGILITY FRACTURE RISKS OF THE FEMORAL NECK

Alexander Tsouknidas[1], Nikolaos Michailidis[2], Kleovoulos Anagnostidis[3] and Antonios Lontos[4]
[1] *Laboratory for Machine Tools and Manufacturing Engineering, Mechanical Engineering Department Aristoteles University of Thessaloniki, Thessaloniki, Greece*
[2] *Physical Metallurgy Laboratory, Mechanical Engineering Department, Aristoteles University of Thessaloniki, Thessaloniki, Greece*
[3] *3rd Orthopaedic Department "Papageorgiou" General Hospital, Aristoteles University of Thessaloniki, Thessaloniki, Greece*
[4] *Department of Mechanical Engineering, Frederick University, Nicosia, Cyprus*

Keywords: Dual-energy x-ray absorptiometry, Femoral neck, FEM, Fragility fracture risks.

Abstract: Osteoporosis is a clinically silent bone pathology usually manifesting in the form of fragility bone fractures. Due to the high morbidity of the disease, the association of noninvasive imaging techniques to the implicated risk factors, could serve as a valuable indicator for surgeons. In the present investigations, the evaluation of 30 patients femurs' bone mineral density was performed in vivo by Dual-energy X-ray absorptiometry (DXA), while the strength characteristics of the examined specimens were determined ex-vivo using uniaxial compression experiments. The obtained stress strain curves, reflect the mechanical properties of the femur while facilitating their correlation to the obtained DXA measurements. FEM simulations revealed critical stress values within the femoral neck, indicating which DXA values represent abnormal high fragility fracture risks and thus should be considered for surgical intervention.

1 INTRODUCTION

Osteoporosis is a multifactorial bone disease concerning roughly 4% of the human population (Melton et al., 1992). As an asymptomatic condition, osteoporosis fails to exhibit noticeable symptoms, particularly at early stages and thus is usually underdiagnosed. Untreated however, this clinically silent disease, is likely to increase the risk of fragility fractures (Ettinger, 2008); (Rockwood et al., 1990); (Cooper et al., 1992). Due to its high morbidity and global nature, osteoporosis is considered a pathology with a significant socioeconomic impact (Ray et al., 1997).

The affected patients' bone mineral density is drastically reduced, deteriorating the bones' micostructural characteristics as a result of excessive bone resorption followed by insufficient bone formation during remodeling (Frost and Thomas, 1963); (Raisz, 2005). The pathogenesis has been associated to dietary aspects (Hackett et al., 2009), immobilization (Minaire, 1989), hyper-parathyroidism (Dupree and Dobs, 2004), vitamin D deficiency (Holick, 2004), alteration of biochemical markers like hormone (Parfitt et al., 1995); (Black et al., 2003) and aging (Newton-John and Morgan, 1970). Regardless etiology, decreased bone mineral density renders the skeletal system susceptibility to fracture, predominantly occurring at the hip (Bohr and Schaadt, 1985), the vertebral column (Old and Calvert, 2004) and wrist (Dempster, 2011).

According to the World Health Organization, osteopenia and osteoporosis are defined by the patient's bone mass deviation, when compared to that of an average, young and healthy adult(WHO, 1994) when measured by DXA.

Even though DXA can accurately determine the minerals and lean soft tissue of the examined area, the overall accuracy of the measurement is impaired by the subtraction of the indirectly calculated fat mass (St-Onge et al., 2004). Furthermore, DXA results are represented as mass per area, thus not considering the anisotropy of the bone tissue and are

Tsouknidas A., Michailidis N., Anagnostidis K. and Lontos A..
DUAL-ENERGY X-RAY ABSORPTIOMETRY AS AN INDICATOR FOR FRAGILITY FRACTURE RISKS OF THE FEMORAL NECK.
DOI: 10.5220/0003770000960101
In *Proceedings of the International Conference on Bioinformatics Models, Methods and Algorithms* (BIOINFORMATICS-2012), pages 96-101
ISBN: 978-989-8425-90-4

hence as a quantitative and not qualitative index of the bone structure(Lochmuller et al., 2000).

Several other methods have been recently introduced to determine bone mineral density (Genant et al., 1996, Braun et al.1998), DXA nevertheless is still widely considered as the method of choice, as techniques like peripheral quantitative computed tomography (pQCT) may be accurate in measuring BMD at peripheral skeletal sites, exhibit however restrictions that prohibit measurements at the proximal femur (Augat et al., 1996); (Augat et al., 1998).

The aim of this investigation is to determine the correlation of the bone mineral density in the femoral neck, as measured by DXA, to experimentally determined strength characteristics of the bone. This, followed by the introduced FEM simulation, will facilitate the use of DXA as an indicator of fragility fracture risk in the hip region, as there is a consensus throughout literature that hip fractures involve the most severe consequences of osteoporotic bone loss.

2 MATERIALS AND METHODS

This study was conducted on femoral neck samples, harvested from patients undergoing total hip replacement due to osteoarthritis. In order to determine the samples' structural integrity, standard X-rays (anterior- posterior) of the pelvis were taken preoperatively in all cases. Patients with a sort femoral neck, large cysts in neck region or previous surgeries in proximal femur were excluded from the study.

Overall 30 patients (27 female and 3 male) were considered as representative candidates for this study and thus subjected to DXA, to catalogue their proximal femur bone mineral density. The average age of these patients was 63.7 years (57- 76 years).

During the surgical procedure and after a 45^o osteotomy, femoral heads were removed and stored at -60oC until evaluation. A plane bone slice with 6mm thickness was harvested from the femoral neck (see figure 1) as two parallel blades, mounted on a mechanical saw at a 6mm distance, simultaneously entered the proximal femur. This ensured similarity among all specimens while producing parallel piped specimens, directly employable in compression tests.

Mechanical testing was performed on an electric INSTRON Testing system. To determine the specimens' strength characteristics, all samples were subjected to uniaxial compression, until failure. A cross-head traveling speed of 0.6mm/s was selected and the maximum travelling distance (upon contact) was set to 5mm in order to avoid contact of the moving cross-head and the fixed base plate. To reduce friction, the sample-actuator contact areas were lubricated. The displacement of the cross-head was measured by means of an inductive sensor, at an accuracy of 1 µm.

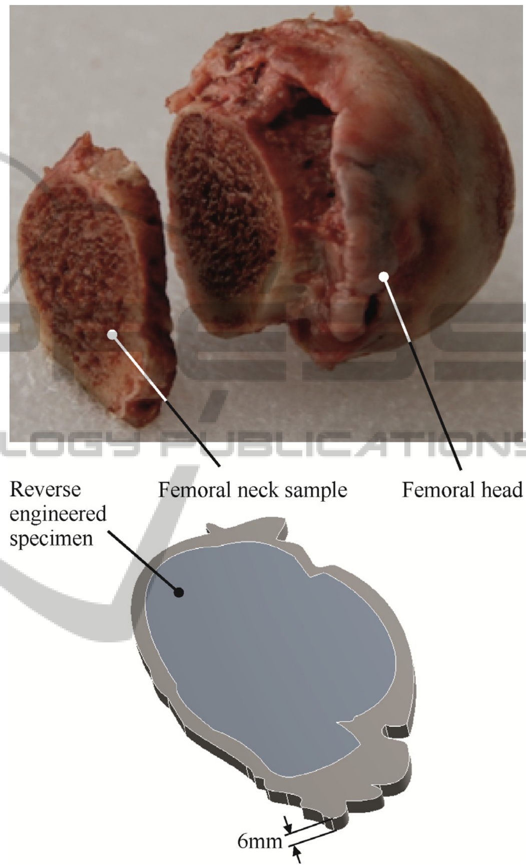

Figure 1: Considered bone specimen and reverse engineered model.

The biomechanical parameters were correlated with BMD using the Pearson correlation coefficient (r) and a linear regression model.

30 experiments were conducted to determine both, compressive yield strength and modulus of elasticity and associate these to the DXA determined T-scores. The T-score compares the measured BMD to that of a young adult (at the age of 35) of the same gender with peak bone mass, while considering statistical values.

3 RESULTS

A correlation of characteristic and mean values

(BMD and T-score) determined by DXA measurements, to the corresponding mechanical properties (yield stress and elastic modulus) of the examined specimens are reflected in table 1. These values are in good coherence with previously presented data (Keller et al., 1990, Reilly and Burstein, 1975). The offset in the determined values can be attributed to the different sampling sites and techniques of the compared studies.

Table 1: Descriptive values concerning BMD, T-score and their correlation to the yield stress (σ_y) and elasticity modulus (E).

	BMD (g/cm^2)	T-score	σ_y (MPa)	E (GPa)
Min.	0.4638	-4.47	109.448	12.643
Max.	0.9694	-0.15	218.02	28.536
Mean	0.7248	-2.218	169.996	20.627
S.D.	0.263		24.843	4.129

A significant dependency of the femoral neck's yield stress and elastic modulus to the measured T-score was affirmed. The highest correlation coefficient was noted for T-score versus maximum failure load (yield stress) of the samples (r=0.838, p<0.001) as illustrated in figure 2.

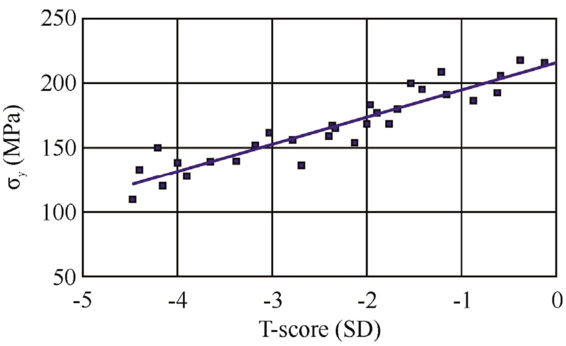

Figure 2: Equivalent T-score values versus yield stress σy (p<0.001).

A similar tendency can be observed for the compressive moduli of the samples, which are calculated based on the linear elastic region of the determined stress-strain curves (Turner and Burr, 1993), as illustrated in figure 3.

A limitation however of the introduced process, is based on the assumption of the material's isotropy and the determination of universal properties of a bone segment comprising of both, cortical and cancellous tissue. This methodology was adopted, as DXA measurements reflect a combined BMA encapturing both bone types by default and thus the assumption of a compound material is beneficiary to the approach.

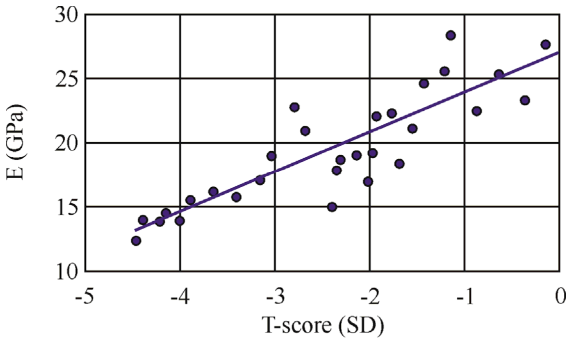

Figure 3: Equivalent T-score values versus elasticity modulus (p<0.001).

4 FEM SIMULATION

In order to associate the ultimate compression strength of the samples, to fragility fracture risks of the femoral neck, the geometry of the specimens was reverse engineered and employed in a linear elastic simulation of a gait type loading scenario considering combined multiaxial forces (Jacobs et al., 1997).

During the simulation, the specimens were once again considered as a uniform-isotropic material, comprising of cortical and cancellous bone tissue, to directly facilitate the correlation of the DXA measurements to the fracture risk of the femoral neck.The experimentally determined mechanical properties were adopted as bulk properties of the compound material and assigned as such in the simulation. The Poisson ratio was assigned as 0,3 corresponding to a mean value of cortical and cancellous bone (Lu and Hutton, 1996, Smit et al., 1997) regardless DXA value.

The acting loads on the femur, comprised of a 2317N joint force (Sarikat and Yildiz, 2011), evenly distributed over the femoral head (inclined by 24^{o} to the frontal plane and 6^{o} to the sagittal one). This force was remotely applied on the upper surface of the reverse engineered specimens at a distance of 46mm corresponding to the mean distance from the tip of the femoral head at which the specimens were severed from the femur. This, based on the coordination system of the model, resulted in a vector force comprising of Fx= 689N, Fy= 942N and Fz= 2001N for axis x, y and z respectively.

The abductor muscle was considered as inactive, as this muscle force acts during the lift up of the foot, thus loading the trochanter during the relaxation of the joint force. As the abductor muscle force has been documented to amount to approximately 703N, the worst case scenario during normal loading of the femur, relates to the aforementioned 2317N joint force.

The acting force and boundary conditions were chosen to mimic the average loading history encountered during walking of an adult human, corresponding to 10.000 daily cycles as described by Sarikat and Yildiz (2011) and are schematically represented in figure 4.

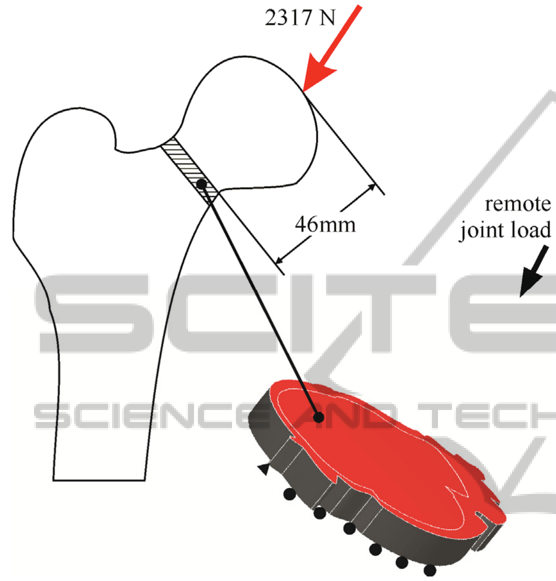

Figure 4: Applied load and boundary conditions of the developed FEM model.

There exists skepticism concerning the ability of compression tests in predicting the hip fracture risk, as fractures in the hip region are the effect of complex dynamic force application, comprising of shear, tension and compression. Based on the forgoing description of the model, it becomes evident that the conducted compression experiments encapture the loading scenario in a realistic manner, as the compressive strength of the femoral neck exerts a dominant impact on the structural integrity of the femur. Furthermore, the compression tests were identically performed in all cases while the only variation between samples was based on the bone mineral density.

A characteristic stress field developing on a femoral neck sample (T-score=-4.47, σ_y=109.448MPa and E=12.6GPa) is demonstrated in figure 5.

5 DISCUSSION

DXA scans in the hip region, are conventionally per-

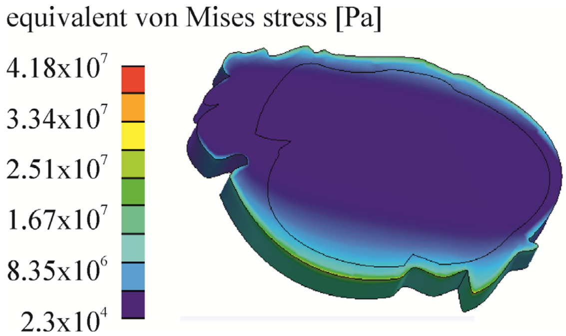

Figure 5: Calculated stress field on a reverse engineered femoral neck sample.

formed in the trochanter, the Ward's triangle and the femoral neck (in an orthogonal area of6 by 10mm). The aim of our study was to correlate the BMD obtained from DXA, to the mechanical strength characteristics of the examined area, as to provide surgeons with a DXA based risk assessment, concerning fragility fractures.

The introduced experimental investigation affirmed the reliability of BMD in predicting the mechanical properties of the femoral neck. A strong enslavement of the ultimate material strength to BMD (r=0.838) was found, while the correlation to elastic modulus (r= 0.689) was weaker.

There exists a consensus throughout literature, that bone density can be considered as a strong independent predictor of failure strength (Stankewich et al., 1996). Considering the foregoing FEM simulation is based on static load representing a daily cycle of at least 10.000 loadings, the maximum developing stress should be multiplied by 3, to account for the fatigue safety factor. By overlaying these fatigue stress value with the experimentally determined fracture strength of the examined specimens, a correlation between T-score and fracture risk can be determined as demonstrated in figure 6.

Even though DXA is a cost efficient BMD determinant, dominating the preference of surgeons due to its simplicity, there are some limitations associated to the method that may affect the accuracy of the introduced procedure.

As DXA quantifies the bone mass and not the bone quality of a specific site, micro-fractures in vertical trabeculae of cancellous bone will maintain undetected. It is however widely accepted, that micro-fractures exert an important influence on the mechanical strength of the bone. Despite this, DXA can be treated as a macroscopically indicator of bone strength. Especially in the hip region, where gait like loading ensures constant remodeling and thus the

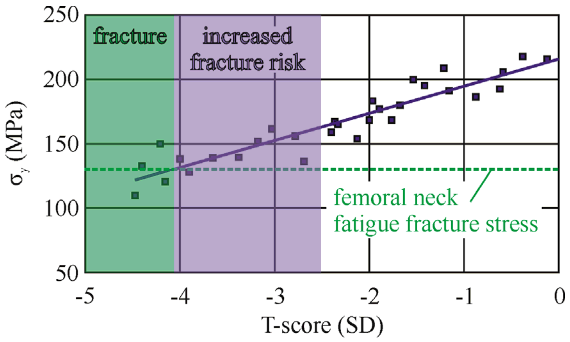

Figure 6: T-score as a fracture risk indicator.

probability of micro fractures is considered as rather low.

Another possible limitation of our study is associated to the patients, the samples were harvested from, as all of them were diagnosed with osteoarthritis. This might have a twofold effect on the BMD-bone properties correlation.

Primary, it has not been established if the most common musculoskeletal disorders of the elderly (osteoarthritisand osteoporosis) may be treated as independent, studies have shown that the presence of one disease may act protective against the other (Solomon et al., 1982, Cooper et al., 1991). The effect however of this on the presented results, can be neglected as the selected patients exhibited significant differences in terms of BMD.

Secondary, osteoarthritis has been associated to subchondral scleroses in femoral head; the femoral neck and the trochander region however, are rarely affected by the condition (Li and Aspden, 1997). In order to circumvent this aspect, our methodology considered DXA scansin femoral neck, trochanter and Ward's triangle and was determinedas reliable. Additionally, osteoarthritic patients undergoing total hip arthroplasty were the only group of patients from whom, we could receive bone samples from the femoral neck region.

Studies have indicated that the femur carries a 30% of the applied loads in the subcapital region, while the base of the neck is subjected by 96% of the total load (Lotz et al., 1995). This strengthens the vital role of the femoral neck's capacity to transmit the compressive stress from the joint to the shaft of the femur. Although the etiology of osteoporotic hip fracture is complex and multifactorial(Melton and Riggs, 1985, Greenspan et al., 1994), bone quality is, without a doubt, a major risk factor.

6 CONCLUSIONS

Bone mineral density measured by DXA, regardless limitations associated to the technique's ability to encapture bone quality, is a strong predictor of bone strength in the femoral neck region. Supported by an adequate FEM simulation, DXA may be regarded as a valuable tool during the prediction of BMD spectrums which present a significant risk of fragility fractures.

REFERENCES

Melton 3rd, L. J., Chrischilles, E. A., Cooper, C., Lane, A. W., Riggs, B. L., 1992. Perspective. How many women have osteoporosis? *Journal of Bone and Mineral Research 7*, 1005-10.

Ettinger, B., 2008. A personal perspective on fracture risk assessment tools. *Menopause: The Journal of The North American Menopause Society 15(5)*, 1023-26

Rockwood, P. R., Horne, J. G., Cryer. C., 1990. Hip Fractures: a future epidemic? *Journal of Orthopaedic Trauma 4*, 388-96.

Cooper, C., Campion, G., Melton, L.J., 1992. Hip fractures in the elderly: A word- wide projection. *Osteoporosis International 2*, 285-9.

Ray, N. F, Chan, J. K, Thamer, M., Melton, L. J., 1997. Medical expenditures for the treatment of osteoporotic fractures in the United States in 1995: Report from the National Osteoporosis Foundation. *Journal of Bone and Mineral Research 12*, 24-35.

Frost, H. M., Thomas, C. C., 1963. Bone Remodeling Dynamics. *Springfield*, IL.

Raisz, L., 2005. Pathogenesis of osteoporosis: concepts, conflicts, and prospects. *Journal of Clinical Investigation 115 (12)*, 3318–25.

Hackett, E. S., MacLeay, J. M., Green, M., Enns, R. M., Pechey, C. L., Les, C. M., Turner, A. S., 2009. Femoral Cortical Bone Mineral Density and Biomechanical. Properties in Sheep Consuming an Acidifying Diet. *Nutrition and Metabolic Insights 1*, 11-6.

Minaire, P., 1989. Immobilization osteoporosis: a review, *Clinical Rheumatology 8 (2)*, 95-103 .

Dupree, K., Dobs, A., 2004. Osteopenia and Male Hypogonadism. *Reviews in Urology 6(6)*, S30–4.

Holick, M. F., 2004. Vitamin D: importance in the prevention of cancers, type 1 diabetes, heart disease, and osteoporosis. *American Journal of Clinical Nutrition 79 (3)*, 362-71.

Parfitt, A. M., Villanueva, A. R., Foldes, J., Rao, D. S., 1995. Relations between histologic indices of bone formation: implications for the pathogenesis of spinal osteoporosis. *Journal of Bone and Mineral Research 10(3)*, 466-73.

Black, D. M., Greenspan, S. L., Ensrud, K. E., Palermo, L., McGowan, J. A., Lang, T. F., Garnero, P., Bouxsein, M. L., Bilezikian, J. P., Rosen, C. J., 2003. The effects of parathyroid hormone and alendronate alone or in combination in postmenopausal osteoporosis. *The New England Journal of Medicine 349(13)*, 1207-15.

Newton-John, H. F., Morgan, D. B., 1970. The loss of bone with age, osteoporosis, and fractures. *Clinical Orthopaedics and Related Research 71*, 229-52.

Bohr, H., Schaadt, O., 1985. Bone mineral content of the femoral neck and shaft: relation between cortical and trabecular bone. *Calcified Tissue International 37*, 340-4.

Old, J. L., Calvert, M., 2004. Vertebral compression fractures in the elderly. *American Family Physician 69(1)*, 111-6.

Dempster, D. W., 2011. Osteoporosis and the burden of osteoporosis-related fractures. *American Journal of Managed Care 17(6)*, S164-9.

World Health Organisation. Assessment of fracture risk and its application to screening for postmenopausal osteoporosis. *Technical Report Series*. Geneva: WHO, 1994.

Genant, H. K., Engelke, K., Fuerst, T., Gluer, C. C., Gramp, S., Harris, S. T., et al., 1996. Noninvasive assessment of bone mineral and structure: State of the art. *Journal of Bone and Mineral Research 11*, 707-30.

Braun, M. J., Meta, M. D., Schneider, P., Reiners, C., 1998. Clinical evaluation of a high-resolution new peripheral quantitative computerized tomography (pQCT) scanner for the bone densitometry at the lower limb. *Physics in Medicine and Biology 43*, 2279-94.

Augat, P., Reeb, H., Claes, L. E., 1996. Prediction of fracture load at different skeletal sites by geometric properties of the cortical shell. *Journal of Bone and Mineral Research 11*, 1356-63.

Augat, P., Fan, B., Lane, N.E, Lang, T. F, LeHir, P., Lu, Y., Uffmann, M., Genant, H. K., 1998. Assesment of bone mineral at appendicular sites in females with fractures of the proximal femur. *Bone 22*, 395-402.

St-Onge, M. P., Wang, J., Shen, W., Wang, Z., Allison, D. B., Heshka, S., Pierson, R. N., Heymsfield, S. B., 2004. Dual-Energy X-Ray Absorptiometry-Measured Lean Soft Tissue Mass: Differing Relation to Body Cell Mass Across the Adult Life Span. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences 59(8)*, 796-800.

Lochmuller, E. M., Miller, P., Burklein, D., Wehr, U., Rambeck, W., Eckstein, F., 2000. In situ femoral DXA related to ash weight, bone size and density and its relationship with mechanical failure loads of the proximal femur. *Osteoporosis International 11*, 361-7.

Turner, C. H., Burr, D. B., 1993. Basic biomechanical measurements of bone: a tutorial. *Bone 14*, 595-608.

Jacobs, C. R., Simo, J. C., Beaupre, G. S., Carter, D. R., 1997. Adaptive bone remodeling incorporating simountaneous density and anisotropy considerations. *Journal of Biomechanics 30(6)*, 603-13.

Keller, T. S., Mao, Z., Spengler, D. M., 1990. Young's modulus, bending strength and tissue physical properties of human compact bone. *Journal of Orthopaedic Research 8*, 592-603.

Reilly, D. T., Burstein, A. H., 1997. The elastic and ultimate properties of compact bone tissue. *Journal of Biomechanics 8*, 393-405.

Lu, Y. M., Hutton, W. C., Gharpuray, V. M., 1996. Do bending, twisting and diurnal fluid change in the disc affect the propensity to prolapse? A viscoelastic finite element model. *Spine 21*, 2570-9.

Smit, T. H., Odgaard, A., Schneider, E., 1997. Structure and function of vertebral trabecular bone. *Spine, 22*, 2823-33.

Sarikat, M., Yildiz, H., 2011. Determination of bone density distribution in proximal femur by using the 3D orthotropic bone adaption model. Proceedings of the institute of Mechanical Engineering, *Part H: Journal of Engineering in Medicine 225*, 365-75.

Stankewich, C. L., Chapman, J., Muthusamy, R., 1996. Relationship of mechanical factors to the strength of proximal femur fractures fixed with cancellous screws. *Journal of Orthopaedic Trauma 10*, 248-57.

Solomon, L., Schnitzler, C. M., Browett, J. P., 1982. Osteoarthritis of the hip: the patient behind the disease. *Annals of the Rheumatic Diseases 41*, 118-25.

Cooper, C., Cook, P. L., Osmond, C., Cawley, M. I. D., 1991. Osteoarthritis of the hip and osteoporosis of the proximal femur. *Annals of the Rheumatic Diseases 50*, 540-2.

Li, B., Aspden, R. M., 1997. Material properties of bone from the femoral neck and calcarfemorale of patients with osteoporosis or osteoarthritis. *Osteoporosis International 7*, 450-6.

Lotz, J. C., Cheal, E. J., Hayes, W. C., 1995. Stress distributions within the proximal femur during gait and falls: implications for osteoporotic fracture. *Osteoporosis International 5*, 252-61.

Melton, L. J., Riggs, B. L., 1985. Risk factors for injury after a fall. Symposium on falls in the elderly: biological and behavioral aspects. *Clinics in Geriatric Medicine 1*, 525-39.

Greenspan, S. L., Myers, E. R., Maitland, L. A., Resnick, N. M., Hayes, W. C., 1994. Fall severity and bone mineral density as risk factor for hip fracture in ambulatory elderly. *Journal of the American Medical Association 271*, 128-33.