AGE- AND SEX-RELATED COMPRESSIVE STRENGTH AND MORPHOMETRY OF LUMBAR VERTEBRAE IN OSTEOPOROSIS

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Abstract: A complex in vitro medical-engineering analysis of human lumbar vertebral bodies L1 and L2 from males and females was investigated in frame of osteoporosis research. Image analyses, CT, MR, densitometry, histology and mechanical tests were executed to clear the relations between mechanical properties, bone architecture and medical parameters of vertebral bone, in terms of aging and sex. From the complex analysis, in this paper the compressive load-bearing characteristics and bone architecture is detailed only. The study aimed to obtain the trends of age- and sex-related change of compressive strength characteristics, bone mineral density, and trabecular architecture, based on compressive mechanical tests and CT images of cadaver specimens.

Introduction

This paper aims to obtain the trends of age- and sex-related changes of compressive strength characteristics in terms of bone mineral density and bone architecture, based on compressive mechanical tests and CT images of cadaver specimens. Compressive strength of cadaver lumbar vertebrae was determined by mechanical tests, and the bone architecture was analyzed on CT pictures. Age-related functions and trends of both strength characteristics and vertebral architecture were obtained for different life periods of osteoporotic elderly, by distinguishing the sexes. As compressive strength parameters limit stresses and strains, Young's elastic moduli, proportional stress and strain limits, ductility and energy absorption capacity were calculated for the human lumbar vertebrae L1 and L2, in terms of aging and sex. The relations with bone architecture based on CT pictures are also detailed.

Materials and Methods

54 cadaver lumbar L1 and L2 vertebrae without posterior elements were obtained from the spine of 16 males and 38 females. The age of males was between 47-87 years (mean age 65,6 year); the age of females was between 43-93 years (mean age 74,2 year).

Before mechanical testing, areal bone mineral density (aBMD), CT and MRI analysis were made for each vertebra. The CT pictures have been used for bone architecture analysis. The CT pictures have been improved by an image analyzer to measure the diameters, the distribution and density of trabeculae in 2D. The measurements have been repeated in the coronal and sagittal plane and in the horizontal cross sectional plane of vertebrae.

For mechanical testing, the two end-plates of vertebrae were cleared away, so that the upper and lower planes of vertebrae be parallel and smooth. In this way, the original height of vertebrae decreased by two times 1-4 mm. The reduced height and the upper and lower cross-sectional areas were measured and registered. The average of the two measured cross sectional areas has been considered as the cross sectional area of each vertebra.

One-way compressive test was carefully performed on each vertebra up to the collapse. No cyclic loading and no unloading were performed. The measuring limit of the tester was 12,5 kN with accuracy of 3%. The compressive deformations were measured in three points, by angle of 120 degree from each other, with 0-5 mm measuring limit.

Loading forces and the occurred displacements between the two end-plates were registered and plotted to a load-displacement diagram. The compressive stresses were obtained as the quotient of the loading force and the cross sectional area. The compressive strains were calculated as the quotient of the shortened and the original height of vertebra. The automatically plotted load-displacement diagrams have been linearized, and the related stress-strain diagrams were classified.

For morphometry analysis, a special program is under development in MATLAB environment for CT image processing tasks, calculating bone parameters by using the picture information (*Kass et al,* 1988).

Results

The two types of typical linearized stress-strain diagrams are illustrated in Fig. 1.

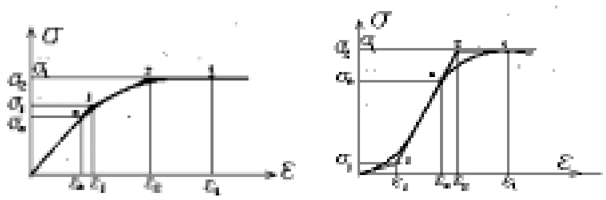

Figure 1: The typical linearized stress-strain diagrams

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Table 1 contains the characteristic values of the stress-strain diagrams in Fig. 1 with the mean values of the given material or geometrical properties and the measured mechanical characteristics of vertebrae. In the first category the mean ages, the areal bone mineral densities, the cross sectional areas and the reduced heights (with removed endplates) are seen, related to the vertebrae L1-L2 together, by distinguishing the sexes. The mean values of areal BMD (males: 0,446, females: 0,347) verify that the analyzed vertebrae belong to the osteoporotic class. Table 1 contains the mean values of measured compressive mechanical characteristics: break loads, proportional stresses and strains, Young's moduli, limit stresses and strains, and energy absorption capacity are illustrated.

Table 1: Mechanical and other characteristics of lumbar vertebrae L1-L2 in compression

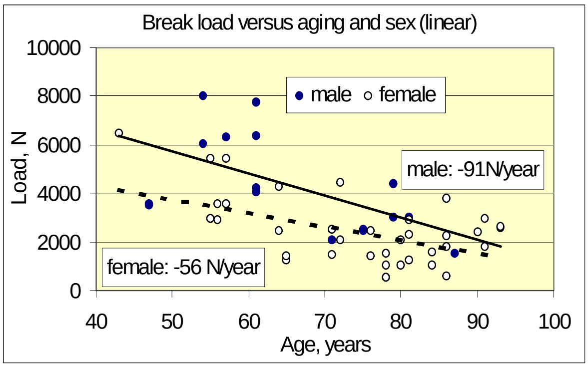
Item	**Male** n=16	**Fem** n=38	**Total** n=54
Mean age	65,6	74,2	71,7
Areal BMD (aBMD)	0,446	0,347	0,376
Cross sectional area	1609	1359	1436
Height without end-plates	21,9	19,0	19,9
Break load	4322	2437	2995
Proportional stress	2,0	1,3	1,5
Proportional strain	3,3	2,9	3,0
Young modulus	91	67	74
Limit stress	2,7	1,9	2,1
Limit strain, ductility	5,0	4,9	4,9
Energy absorption cap.	1,63	0,97	1,18

Figs 2 and 3 illustrate the linear and quadratic approximation of the age-related decline of measured break loads and calculated limit stresses of vertebrae L1-L2, between 43-93 years, by distinguishing the sexes.

Figs 4 and 5 illustrate the linear and quadratic approximation of the age-related decline of Young's moduli and energy absorption capacity of vrtebrae L1-L2, between 43-93 years, by distinguishing the sexes.

By using linear approximation for age-dependence seen in Figs 2a, 3a, 4a and 5a, the numerical values of decrease trends, namely, the so-called age-sensitivity, that is, the decrease for a year of aging can be obtained. Table 2 illustrates the age-sensitivity values (for the total analyzed age span 43-93 years), related to the main strength parameters, that is, break loads, limit stresses, Young's moduli and energy absorption capacity. However, by applying linear approximation, the different decrease tendencies in different age periods can not be studied.

By using quadratic approximation, seen in Figs 2b, 3b, 4b and 5b, significant decrease can be distinguished for men and women in different life period.



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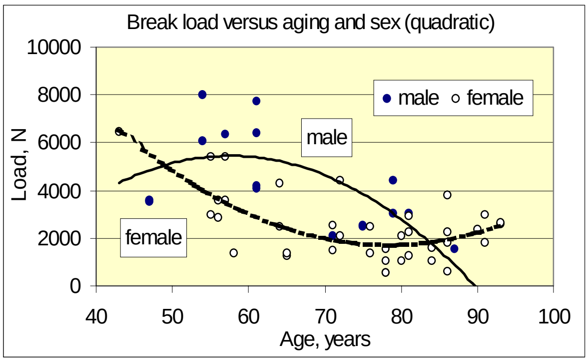

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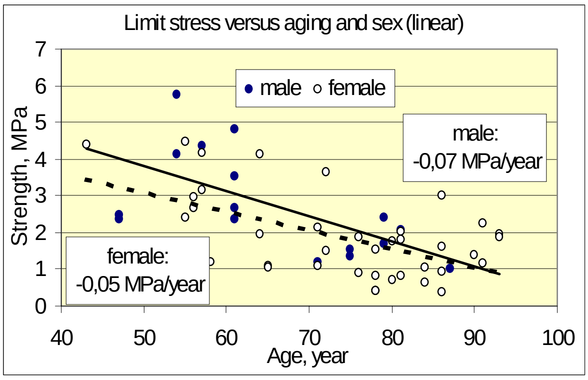
Figure 2: a) Linear and b) quadratic approximation of age-related decline of break load of vertebrae L1-L2



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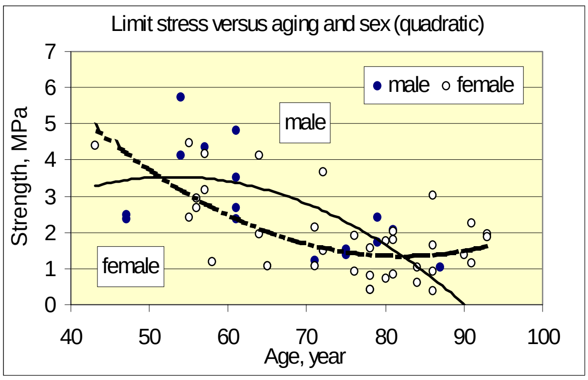

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Figure 3: a) Linear and b) quadratic approximation of age-related decline of limit stress of vertebrae L1-L2

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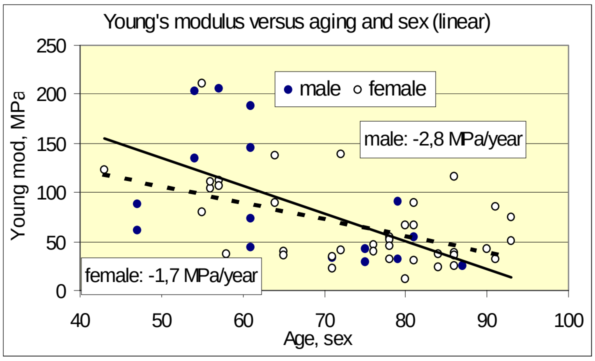

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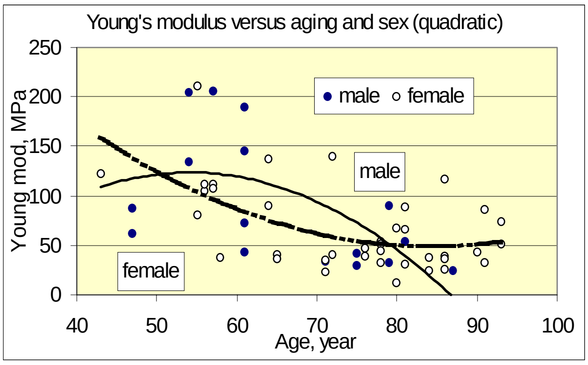

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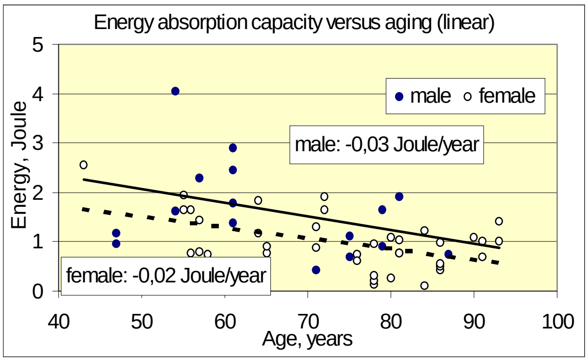
Figure 4: a) Linear and b) quadratic approximation of age-related decline of Young mod. of vertebrae L1-L2



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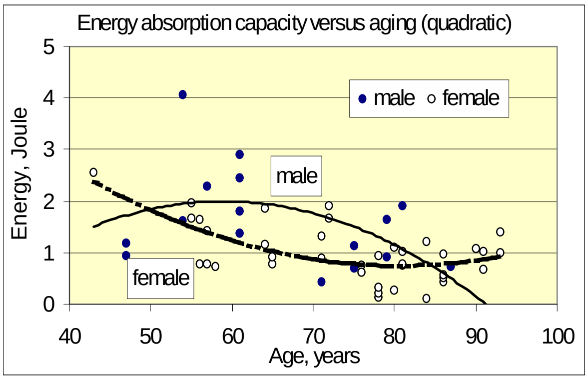

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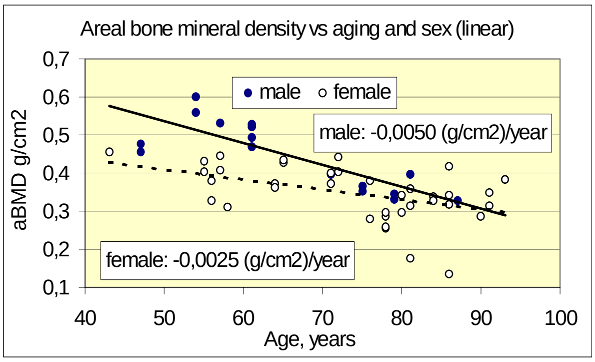
Figure 5: a) Linear and b) quadratic approximation of age-related decline of energy absorption capacity of vertebrae L1-L2

Table 2: Decrease trends of compressive mechanical characteristics with aging

Item		**Male** n=16	**Fem** n=38	**Total** n=54
Break load	N/year	-91	-56	-80
Limit stress	MPa/year	-0,07	-0,05	-0,06
Young mod.	MPa/year	-2,8	-1,7	-2,1
Energy abs.	Joule/year	-0,029	-0,022	-0,028

Fig. 6 illustrates the age-related decrease of the areal bone mineral density (aBMD) of the measured vertebrae. Linear approximation in Fig. 6a provides the bone loss per a year, quadratic approximation in Fig. 6b shows the different decrease trends in different age-periods.



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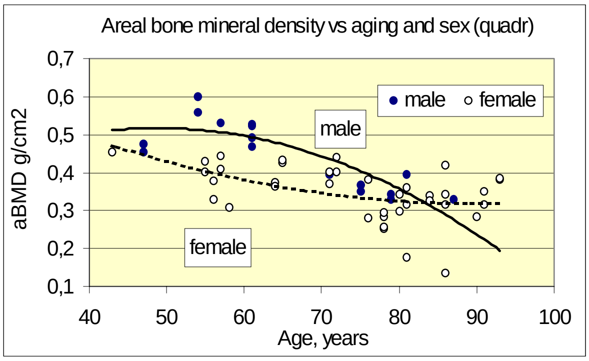

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Figure 6: a) Linear and b) quadratic approximation of age-related decline of areal bone mineral density (aBMD) of vertebrae L1-L2

Table 3 contains the correlation coefficients of aBMD and the compressive mechanical strength characteristics with aging, related to the unified vertebrae L1 and L2, by distinguishing the sexes.

Table 4 contains the correlation coefficients of the compressive mechanical strength characteristics with aBMD related to the unified vertebrae L1 and L2, by distinguishing the sexes.

In Fig. 7 the decrease of trabecular relative bone volume (BV/TV) is illustrated in terms of aging. Values of BV/TV have been calculated both for the upper third level of vertebrae having higher, and for the middle third level having lower density of trabeculae.

Table 3: Correlation between aging and biomechanical parametes of lumbar vertebrae L1-L2 in compression

Item	**Male** n=16	**Fem** n=38	**Total** n=54
Areal BMD	-0,82	-0,47	-0,63
Cross sectional area	0,54	0,44	0,26
Break load	-0,57	-0,52	-0,59
Limit stress	-0,62	-0,57	-0,62
Limit strain, ductility	-0,00	-0,20	-0,16
Young modulus	-0,55	-0,52	-0,55
Proportional stress	-0,64	-0,55	-0,62
Energy absorption cap.	-0,37	-0,51	-0,50

Table 4: Correlation between aBMD and biomechanical parametes of lumbar vertebrae L1-L2 in compression

Item	**Male** n=16	**Fem** n=38	**Total** n=54
Cross sectional area	-0,45	-0,40	-0,03
Break load	0,80	0,47	0,70
Limit stress	0,84	0,48	0,66
Limit strain, ductility	0,23	0,38	0,31
Young modulus	0,75	0,32	0,53
Proportional stress	0,84	0,39	0,63
Energy absorption cap.	0,64	0,57	0,67

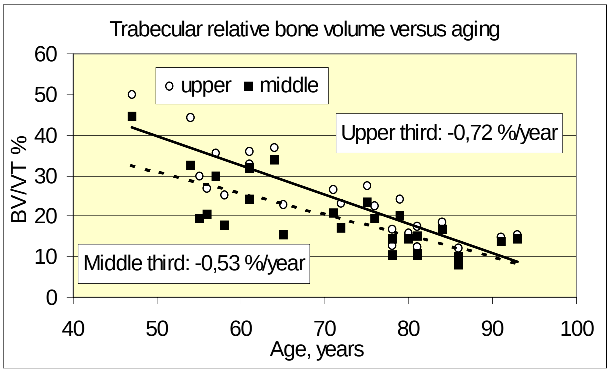

Figure 7: Decrease of trabecular relative bone volume (BV/TV) with aging

In Fig. 8 the increase of break load with increasing BV/TV can be seen.

In Fig. 9 the relation between trabecular relative bone volume (BV/TV) and energy dissipation capacity can be seen.

Table 5 shows the correlation between BV/TV and the biomechanical parametes of lumbar vertebrae L1-L2 in compression.

Table 5: Correlation between BV/TV and the biomechanical parametes of lumbar vertebrae L1-L2 in compression

Item	**Upper** n=26	**Middle** n=26
Age	-0,87	-0,76
Break load	0,59	0,50
Limit stress	0,58	0,48
Limit strain, ductility	0,20	0,17
Young modulus	0,48	0,37
Energy absorption cap.	0,47	0,38

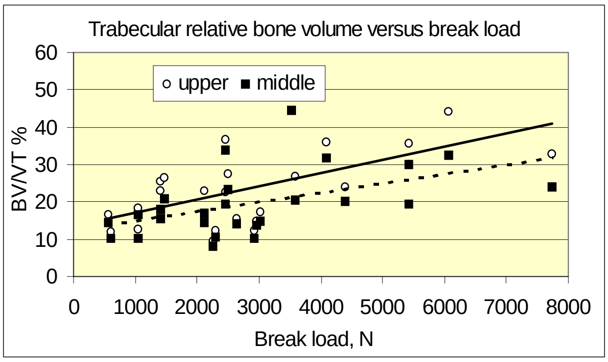

Figure 8: Relation between trabecular relative bone volume (BV/TV) and break load of lumbar vertebrae L1-L2 in compression

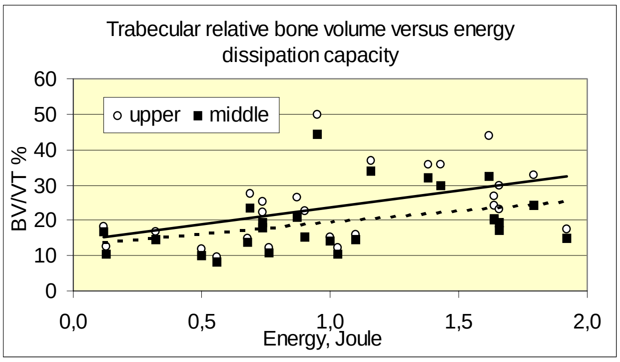

Figure 9: Relation between trabecular relative bone volume (BV/TV) and energy dissipation capacity of lumbar vertebrae L1-L2 in compression

Discussion and Conclusions

Significant difference has been found in the load bearing properties of sexes. The compressive load bearing capacity of women was about 30% smaller than that of the men (Table 1). Break load and limit stress of women were 40-45% smaller, Young's moduli of women was 20-30% smaller than that of the man. At the same time, there were no significant sex-differences in the proportional or limit strains and in ductility. However, there was a significant difference again in the energy absorption capacity of men and women: women had about 40% smaller absorption capacity than men,

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that can be dangerous in aspect of injuries due to accidental loads. This comes partly from the smaller limit stresses and partly from the smaller volume of vertebrae of females.

Lindahl (1976) and *Hansson et al.* (1987) obtained for cancellous bone of lumbar vertebrae, as follows: for proportional stress 1,37-4,0 MPa, for the proportional strain 6,0-6,7%, for the Young's modulus 22,8-55,6 MPa, for the limit stress 1,55-4,60 MPa, and for the limit strain 7,4-9,5%. These results concern the cancellous core of vertebrae, proving that due to the high ductility, the trabecular bone is responsible for the energy absorption ability of vertebrae, in avoiding injury. Based on compressive tests of lumbar vertebrae, *Tanaka et al.* (2001) found the value of limit stress between 0,14-4,54 MPa.

Based on his combinative study *Mosekilde* (2000) demonstrated that the age is the major determinant of vertebral bone strength, mass, and microarchitecture. There is, after the age of 50 years, a higher tendency for disconnection of the trabecular network in women than in men.

By applying linear approximation between the age of 43-93 years for the age-related behaviour of all strength characteristics, it can be observed that both the aBMD and the age-related decrease trends of women are smaller than that of men. In this way, age-sensitive decrease trends can be calculated numerically for each strength parameter seen in Table 2, also for sex-independent cases.

As a conclusion of our experiments, during the age period between 40-90 years, the strength properties decrease by 60-70% for both sexes. According to the linear regression analysis of *McCaldren et al* (1997) related to the age-dependent changes in the compressive strength of cancellous bone of 255 femoral cadaver specimens from donors in age of 20 to 102 years, the compressive strength decrease yields 8,5% in each decade of aging. This means that the 80 years long decrease period yields 68% of total strength decrease. *Mosekilde* (1998) also mentioned that the decline in strength of the whole vertebral body during normal aging for both men and women is 70-80%. These results are in agreement with our results.

However, from the above observations it became evident that a nonlinear approximation is needed to clear the fact that in certain age period women and men have different strength loss.

By applying quadratic approximation, typical "fish-like" curves are obtained for sexes equally for both the mechanical parameters and for mineral density, seen in Figs 2b - 6b. These curves verify that the strength loss starts earlier and lasts longer in women than in men. While in women the strength decrease happens between 50-80 years, for men it takes place between 60-80 years. The highest value of age-sensitivity (decrease/year) in women happens in the beginning of the decrease period, at about 45-50, while for men it happens at the end of the decrease period, closed to 80.

Since the load-bearing capacity decreases with aging, obviously, there is a significant negative correlation between almost all strength parameters and aging, seen in Table 2. Except for energy absorption capacity and ductility of vertebrae, men have higher correlation than women, thus, men seem to be more age-sensitive than women. These results agree with the results of *Mori* (1994) that found the correlation between aging and compressive Young's modulus of normal patients as -0,527, based on compression tests of bone samples of vertebra L3. Similarly, based on compressive tests of lumbar vertebrae, *Tanaka et al.* (2001) found the correlation significant, namely, -0,66 between limit stresses and aging.

As seen in Fig. 6, the analyzed vertebrae belong to the strongly osteoporotic class. Since the indicator of bone loss is the mineral density, naturally, there is a significant positive correlation between almost all strength parameters and aBMD. Except for ductility, the correlation is higher again in men than in women.

The analysis of vertebral morphometry is under development this time. The first results verify that the between the parameters of the bone architecture and the measured mechanical compressive strength characteristics are in a significant correlation. Trabecular diameter and trabecular relative bone volume ratio (BV/TV) were calculated for the middle level and for the upper and lower levels of vertebrae, in terms of aging and mechanical charateristics.

There is a significant negative correlation between aging and trabecular architecture, seen in Fig. 7 and Table 5. For the upper and lower level of vertebrae where the density of trabeculae is higher, a better correlation exists with all parameters than in the middle level, seen in Table 5.

As seen in Fig. 8, the break load (and all the derived other strength parameters, like limit stress, Young's modulus, and energy dissipation capacity) increase with increasing bone ratio BV/TV.

Energy dissipation, seen in Fig. 9 is also increasing with better bone conditions, which has a great importance in the case of accidental loading to avoid injuries. This fact is even more important for highly osteoporotic vertebrae, where the risk of fracture is even higher.

The morphometry analysis of vertebrae is under work, the effect and ratio of cortical and trabecular load bearing capacity is to be analyzed with the effect of sex and aging.

Acknowledgements

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