COMPRESSIVE LOAD-BEARING AND BONE ARCHITECTURE OF LUMBAR VERTEBRAE IN TERMS OF SEX AND AGING

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1. ABSTRACT

Relation between vertebral compressive strength and trabecular architecture is presented in terms of aging and sex. Complex in vitro medical-engineering analysis of cadaver human lumbar L1 and L2 vertebrae was executed: densitometry, CT, MRI, mechanical test and histology, in aspect of osteoporosis. In this paper the results of the mechanical test are detailed only. The compressive mechanical parameters, like limit stress and strain, proportional stress and strain, Young modulus, ductility, energy absorption capacity were determined. Morphometry analysis was based on the CT pictures. Density and diameter of trabeculae were measured. Correlation between morphometric and mechanical properties was evaluated in terms of aging, sex and bone mineral density.

2. INTRODUCTION

Compressive strength of cadaver lumbar vertebrae was determined by mechanical tests, and compared with the morphometry of the trabecular bone of vertebrae. One-way compressive test was carefully performed on each vertebra up to the collapse. The automatically plotted load-displacement diagrams were evaluated. Age- and sex-related functions and trends of both strength characteristics and vertebral architecture were obtained. Limit stresses and strains, Young's elastic moduli, proportional stresses and strains, 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 were based on CT pictures.

This paper aims to obtain the trends of age- and sex-related change of compressive strength characteristics, in terms of bone mineral density and trabecular architecture. The results can be used in numerical simulation of osteoporotic processes.

3. 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); of females was between 43-93 years (mean age 74,2 year).

Keywords: lumbar vertebrae, compressive test, morphometry, BMD

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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. The reduced height and the upper and lower cross-sectional areas were measured and registered.

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 were linearized, and the related stress-strain diagrams were classified.

3. RESULTS

Table 1 and 2 contains the mean values of measured and calculated mechanical characteristics of vertebrae L1 and L2, respectively, by distinguishing the sexes.

Mean mechanical characteristics of lumbar vertebrae L1in compression		**Males** n=10	**Females** n=21	**Total** n=31
Proportional stress σ_p	MPa	2,0	1,4	1,6
Proportional strain ε_p	%	3,6	2,9	3,2
Young modulus E	MPa	92	74	80
Limit stress σ_u	MPa	2,8	2,1	2,3
Limit strain, ductility ε_u	%	5,3	5,1	5,2
Energy absorption capacity	Joule	1,58	1,03	1,21

Table 1: Mechanical characteristics of lumbar vertebrae L1 in compression

Mean mechanical characteristics of lumbar vertebrae L2 in compression		**Males** n=6	**Females** n=17	**Total** n=23
Proportional stress σ_p	MPa	1,9	1,0	1,3
Proportional strain ε_p	%	2,8	2,5	2,7
Young modulus E	MPa	89	57	65
Limit stress σ_u	MPa	2,7	1,6	1,9
Limit strain, ductility ε_u	%	4,6	4,7	4,7
Energy absorption capacity	Joule	1,71	0,95	1,15

Table 2: Mechanical characteristics of lumbar vertebrae L2 in compression

In Table 1 and 2, the proportional stresses and strains, Young's moduli, limit stresses and strains and energy absorption capacity are illustrated.

In Fig. 1 the linearized stress-strain diagrams of unified vertebrae L1-L2 are seen with the relating characteristic points and values, for males and females together.

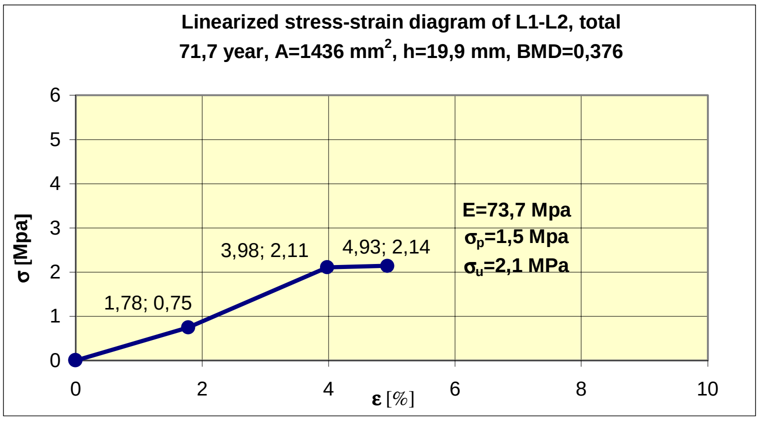


Figure 1: Linearized stress-strain diagrams of vertebrae L1-L2

Figs 2 and 3 illustrate the linear 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. The decrease trends are also given numerically.

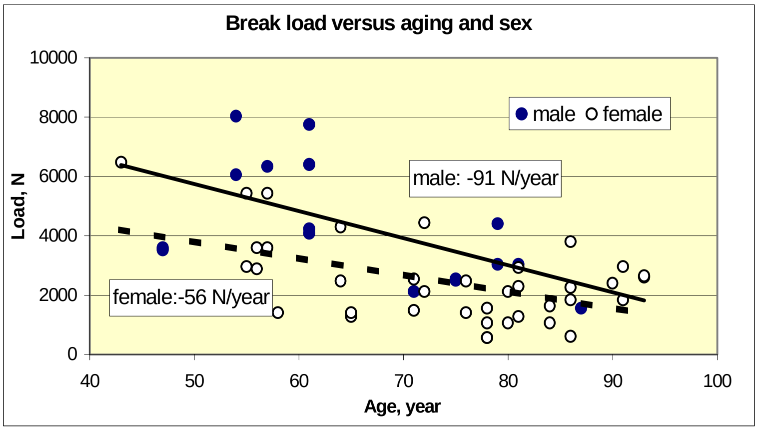


Figure 2: Linear age- and sex-related decline of break load of vertebrae L1-L2

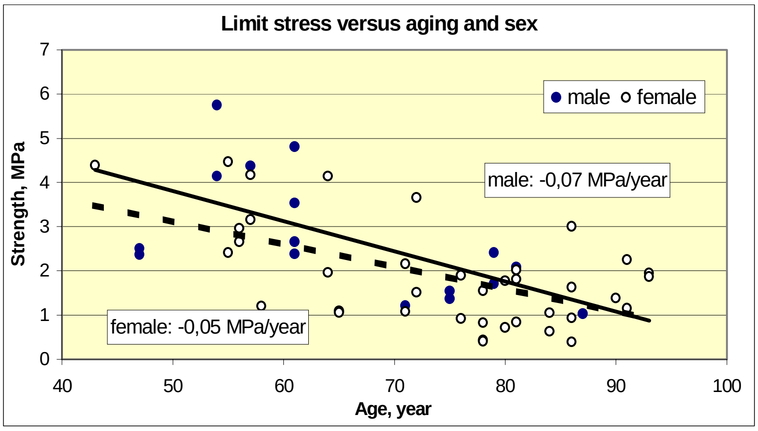


Figure 3: Linear age- and sex-related decline of limit stresses of vertebrae L1-L2

In Figs 4 and 5 the Young's moduli and the energy absorption capacity are illustrated in terms of aging, by distinguishing sexes. The decrease trends are also given numerically.

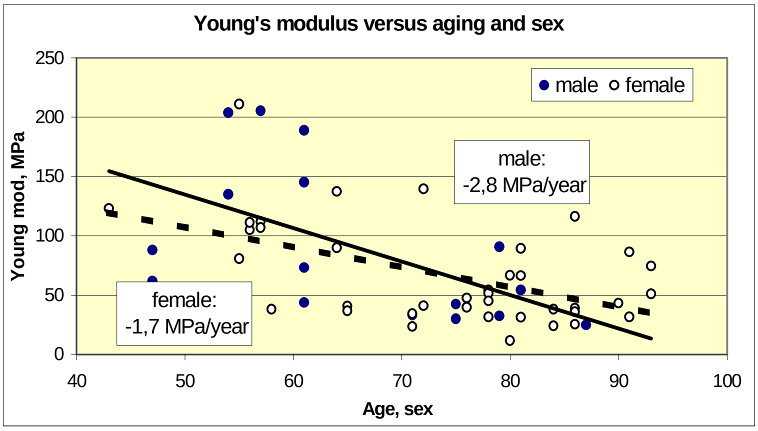


Figure 4: Linear age-related decline of Young's moduli of vertebrae L1-L2

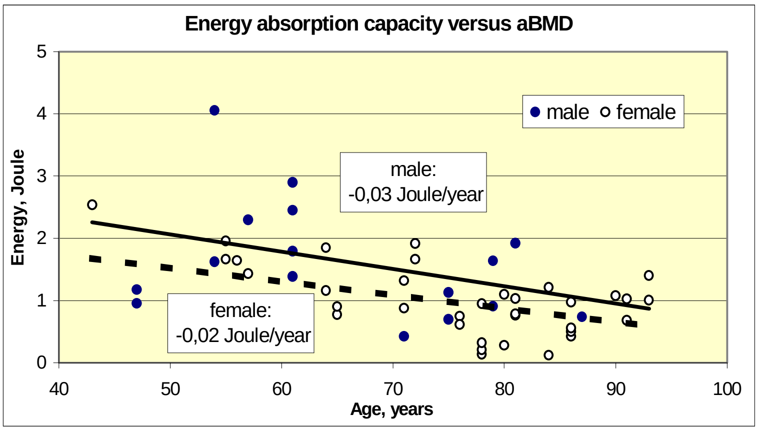
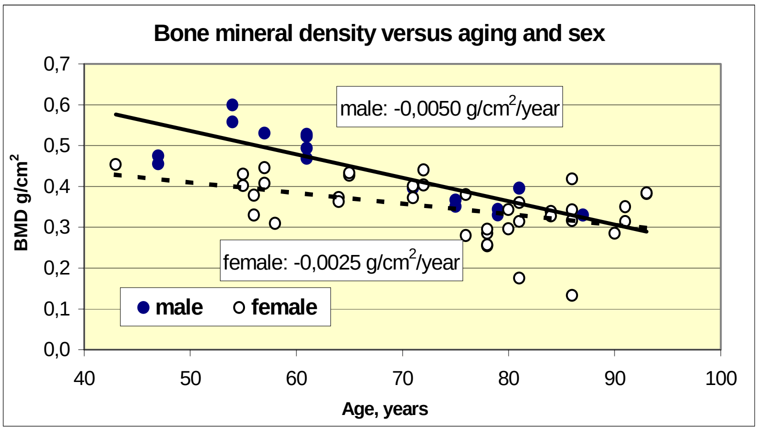


Figure 5: Linear age-related decline of energy absorption capacity of vertebrae L1-L2

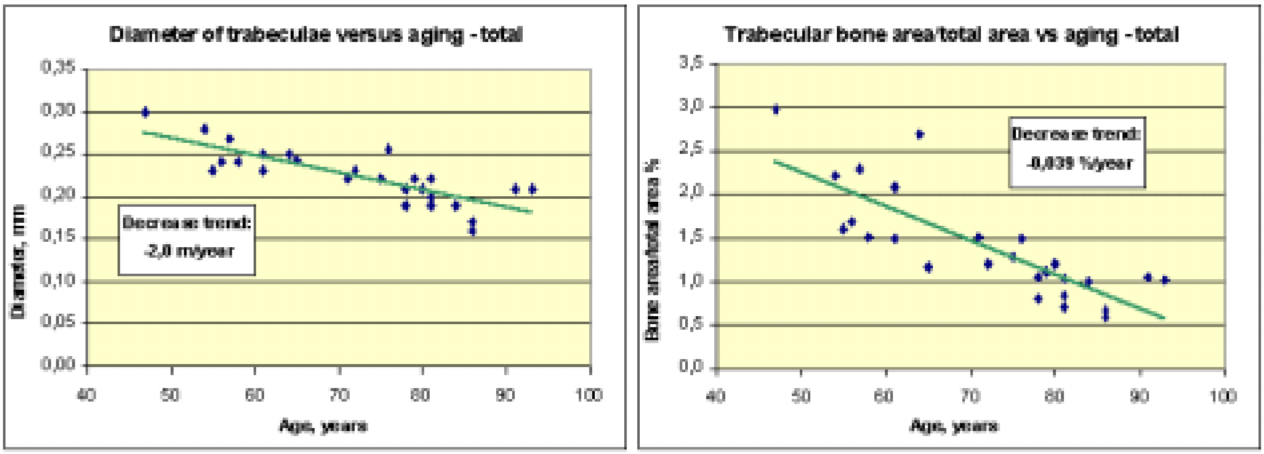


6: Linear age-related decline of areal bone mineral density of vertebrae L1-L2

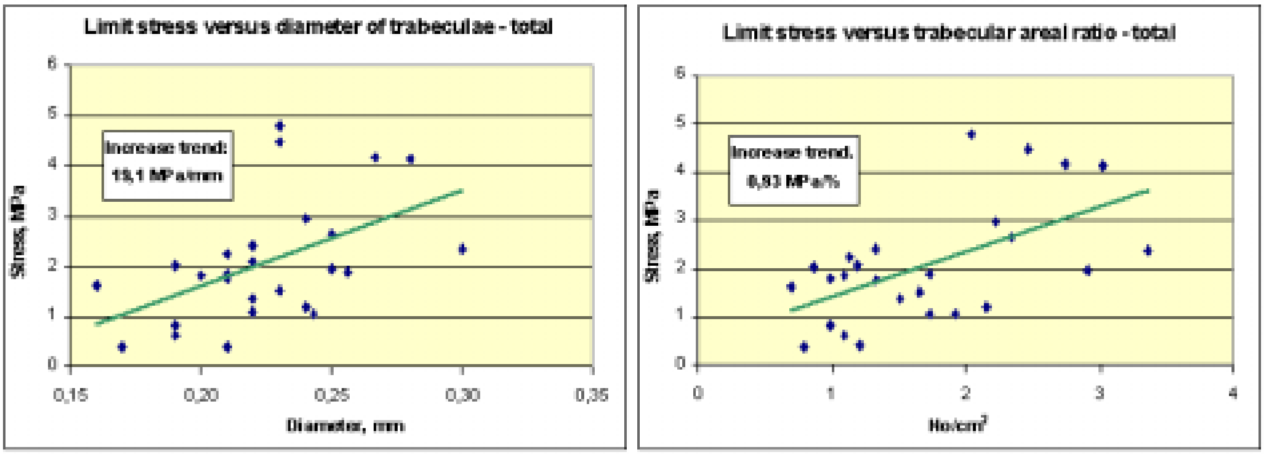
Fig. 6 illustrates the age-related decrease of the areal bone mineral density (aBMD) of the measured vertebrae. Linear approximation is supposed to obtain the bone loss per a year.

In Fig. 7 the age-related decrease of parameters of the trabecular architecture is illustrated. Linear approximation of age-dependence of trabecular diameters, the ratio of trabecular bone area over total area of vertebral cross section are illustrated.

In Fig. 8 the linear approximation of the increase of limit stress in terms of the diamater and areal ratio of trabeculae can be seen.



7: Linear age-related decrease of trabecular architecture of vertebrae L1-L2



8: Linear increase of limit stress vs trabecular architecture of vertebrae L1-L2

4. DISCUSSION AND CONCLUSION

As a result of the compression tests, there is a 15-18% decrease in the compressive load bearing properties, in stress and strain moduli in distal direction. There is a significant difference in the load bearing properties of males and females, namely, the compressive load bearing capacity of women is about 30% smaller than that of the men. The break load of women is 40-50% smaller. Moreover, since the cross sectional areas of women are only 15% smaller, consequently, both the proportional and limit stresses are 30-40% smaller in women than in men. The Young's moduli of women are about 20-30% smaller than that of the man. At the same time, there is no significant sex-difference in the proportional or limit strains and in the duclility. However, there is a significant difference again in the energy absorption capacity of men and women: women have about 35-45% smaller absorption capacity than men. This comes partly from the smaller limit stresses and partly from the smaller volume of vertebrae of females.

The results of *Lindahl* (1976) and *Hansson et al.* (1987) concern the cancellous core of vertebrae, proving that due to the high ductility, there is the trabecular bone that is responsible for the energy absorption ability of vertebrae to avoid the injury in the case of an accidental dynamical load. *Mosekilde* (2000) emphasized that a basic understanding of age-related changes in the quality and strength of vertebral bone is crucial. Based on his combinative study he 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 trabecular network in women than in men.

By applying linear approximation for the age-related behaviour of all strength characteristics, it can be observed that the decrease trends of women are smaller than that of men, seen in Fig. 2 for break load, in Fig. 3 for limit stress, in Fig. 4 for Young's modulus and in Fig. 5 for energy absorption capacity.

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), 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.

As seen in Fig. 6, the analyzed vertebrae belong to the strongly osteoporotic class. It can be concluded that the areal bone minearal density decrease significanly with aging. The decrease trend can be numerically verified by applying linear approximation. All compressive strength parameters increase significantly with bone mineral density, or, inversely, decrease significantly with the age-related decrease of aBMD. Fig. 7 illustrates the age-related weakening of trabecular architecture, namely, the loss of trabecular diameter and the parameters of several trabecular areal ratio. Fig 8 verifies numerically the effect of trabecular architecture on the compressive strength of vertebrae in osteoporosis.

In this study the compressive strength of osteoporotic lumbar vertebrae has been numerically verified in terms of aging, sex and bone structure, based on mechanical tests.

5. REFERENCES

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