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Original Paper

Relationships between structure, density and strength of human trabecular bone

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The article deals with the examination of the relationships between density, structure parameters and strength of human trabecular bone. The tests were carried out on the samples taken from osteoporotic and coxarthrotic human femoral heads. The samples cylindrical in shape had the diameters of 10 mm and the height of 8.5 mm. During the tests with μCT scanner the parameters of a sample structure were measured. Bone mineral density (BMD) was measured as well. The samples were subjected to compression in order to assess the ultimate compression strength σ_c. The relationships between two-element combinations (BMD and one of the structure parameters) and the compression strength of the samples have been studied. The consistence of the results for multiple regression and response surface regression was estimated based on the correlation coefficient *R*. For the examined pairs of parameters, the value *R* increased in the range of 7÷30% in comparison with the case where for the strength description only BMD was used. Additionally, the authors' own models of two-variable regression was calculated. The comparison of the results obtained for all models of regression based on the coefficient *E* proved the consistence of these results.

Key words: *architecture of trabecular bone, BMD, strength of trabecular bone*

1. Introduction

In the clinical practice, the basic examination allowing a bone quality to be estimated is the measurement of bone mineral density (BMD) [1], [2]. On the basis of the values of BMD and BMC (bone mineral content) (in medical practice mainly *T*-score, *Z*-score) parameters obtained experimentally an indirect evaluation of the strength of bone is also possible. During in vitro examinations of bone, BMD is one of parameters used to estimate the strength of bone [2]–[5] based on the measurement of its mineral content. Because of the weakness of this approach, the architecture of trabecular bone, e.g. amount of trabeculaes, their thickness or volume orientation, cannot be described.

Actually, the techniques based on high-resolution imaging of bone, e.g. MRI or μCT [6]–[10], are more and more accessible. These methods allow us to establish an exact structure of bone. The parameters describing the structure obtained experimentally are also used for the description of bone strength [6], [11]. On the basis of the images from μCT or MRI it is also possible to build micromechanical models used to estimate mechanical properties of bone in FE analysis [12], [13].

Some authors [12], [14] report that at the same density or volume fraction the structure of trabecular bone can be quite different. Hence, presently, in the papers dealing with the strength of trabecular bone, their authors are of the opinion [15]–[17] that the strength of a trabecular bone depends not only on its density but also on the structure. Therefore, we attempt to answer the following questions:

- What is the usability of structure parameters for the description of bone strength?
- What is the consistence of strength description by means of structure parameters compared with its description by BMD?

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• Will two-element combinations of different parameters result in a better strength description compared with the description only by BMD or by structure parameters?

2. Material and methods

The tests were carried out on 42 samples taken from a femoral bone head: 21 samples from osteoporotic bone and 21 from coxarthrotic bone. In the first stage, the slices of about 8.5-mm thickness were cut from the base of head, perpendicularly to the axis of the neck of bone. Next, from a central region of the slice a cylindrical sample, about 10 mm in diameter and 8.5 mm in height, was cut out. The manner of collecting and shaping the sample is presented in figure 1.

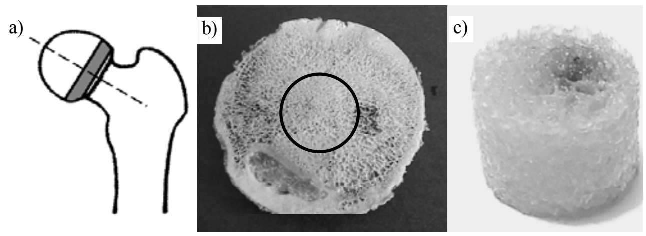

Fig. 1. Manner of collecting sample:
a) cutting slice, b) cutting sample, c) sample

During examination the BMDs of the samples were estimated. BMD was measured by DEXA method (dual-energy X-ray absorptiometry) using Lunar Expert scanner (General Electric Company). During μCT examination (μCT80 scanner, Scanco Company) the values of the sample structure parameters were determined. The scanning resolution was 36 μm and we obtained about 230 images of the bone structure per sample. The following structure parameters were measured [18]:

- Tb.N – trabecular number, 1/mm,
- Tb.Th – trabecular thickness, mm,
- Tb.Sp – trabecular separation, mm,
- BS/BV – bone surface/bone volume, 1/mm,
- BV/TV – bone volume/trabecular volume.

In the next stage, a compression test was performed. The first five loops in an elastic range of 0÷0.8% were done, with a 5-second pause between the loops, next the test was carried out to achieved the ultimate compression strength σ_c. The strain rate was 0.1% per second. The compression test was conducted using MiniBionix858 testing device.

The equations representing the relationships between density and module or strength are given in [19]–[22] in the form of linear, power or exponential equations. On this basis, our additional regression models accounting only for a combination of two variables were proposed. The authors have derived the possibly simple equations with no more than two variables, which are based on the relationships described in [19]–[22]. The equations representing our models were presented in table 1. Then, the analysis of regression for two variables, i.e. density and selected structure parameter, was carried out. The main reason we adopted such an approach was because of an easier interpretation of two variables, compared with more variables in clinical practice. An additional limitation was the number of samples in each group examined. Statisitcal calculations were done with Statistica software (StatSoft Company). For the validity of results, the number of the samples had to be about 10 times higher than the number of variables in analysis.

Table 1. Equations of our own regression models

No.	Formula
I	σ_c = (B1*v1^B2)*(B3*v2^B4)
II	σ_c = (B1*v1^B2)+(B3*v2^B4)
$v1$, $v2$ – variables B1, B2, B3, B4 – number coefficients	

3. Results

The results of measurements in both groups of samples are presented in table 2. The table contains the range, mean values, and standard deviation of the results in both sample groups under examination.

In table 3, there are presented the absolute values of the correlation coefficient R for a linear regression for density, selected structure parameters and bone strength.

In the following step, a two-variable regression model was built in such a way that each pair contained BMD and one of the structure parameters. A two-variable regression model was run using multiple regression, response surface regression and regression according to authors' own models. Table 4 presents the pairs of the parameters for which the highest values of the correlation coefficient R for multiple regression and response surface regression were achieved. For every model of regression, the diagram of the values obtained in the experiment versus the predicted ones,

Table 2. Range, mean value and standard deviation of the results in both groups of samples

Osteoporosis				Coxarthrosis			
Parameter	Range	Average	SD	Parameter	Range	Average	SD
BMD, g/cm^2	0.115÷0.343	0.197	0.051	BMD, g/cm^2	0.186÷0.404	0.289	0.069
Tb.N, 1/mm	0.760÷1.680	1.290	0.229	Tb.N, 1/mm	0.961÷1.958	1.582	0.219
Tb.Th, mm	0.089÷0.230	0.139	0.031	Tb.Th, mm	0.113÷0.259	0.164	0.037
Tb.Sp, mm	0.380÷1.223	0.664	0.192	Tb.Sp, mm	0.331÷0.928	0.481	0.124
BV/TV	0.068÷0.377	0.185	0.071	BV/TV	0.109÷0.392	0.260	0.070
BS/BV, 1/mm	8.686÷22.505	15.024	3.080	BS/BV, 1/mm	7.737÷17.646	12.783	2.604
σ_c, MPa	2.329÷13.105	7.046	3.052	σ_c, MPa	1.678÷25.288	13.366	6.448

Table 3. Absolute values of correlation coefficient R for σ_c

Parameter	R	
	Osteoporosis	Coxarthrosis
BMD, g/cm^2	0.81	0.71
Tb.N, 1/mm	0.61	0.31
Tb.Th, mm	0.47	0.79
Tb.Sp, mm	0.61	0.59
BV/TV	0.59	0.76
BS/BV, 1/mm	0.45	0.81

Table 4. The highest values of R for particular pairs of parameters and strength in both groups of samples

Sorting according to multiple R			Sorting according to response surface R		
Parameters v_1, v_2	Multiple regression	Response surface regression	Parameters v_1, v_2	Multiple regression	Response surface regression
	Multiple R	Response surface R		Multiple R	Response surface R
Osteoporosis					
BV/TV–BMD	0.81	0.87	BV/TV–BMD	0.81	0.87
Tb.N–BMD	0.81	0.85	Tb.N–BMD	0.81	0.85
Tb.Sp–BMD	0.81	0.85	Tb.Sp–BMD	0.81	0.85
Coxarthrosis					
Tb.Th–BMD	0.86	0.92	Tb.Th–BMD	0.86	0.92
BS/BV–BMD	0.86	0.91	BS/BV–BMD	0.86	0.91
BV/TV–BMD	0.83	0.87	BV/TV–BMD	0.83	0.87

i.e. those obtained from calculations based on regression, was drawn. For the pairs of the highest values of the coefficient R in each other group of samples (table 3) the diagrams are presented (figures 2–3).

In order to assess whether the values of the coefficient E calculated from the model are consistent with measured values, the method reported in [23] was used. E is used to estimate the agreement of the results obtained using different models of regression. This coefficient is defined by:

$$E = \frac{((1-|a|)+(1-|1-b|)+(1-|1-a-b|)+(1-|1-R|))}{4}, \tag{1}$$

where:

a – the free term of regression equation from the diagram of measured versus predicted values (figures 2 and 3),

b – the coefficient of regression equation from the diagram of measured versus predicted values,

R – the correlation coefficient from the diagram of measured versus predicted values.

The coefficient E accounts for the coefficient R (from the diagram of measured versus predicted values for a model of regression) and the coefficients a and b from the diagram. The value of this coefficient ranges from 0 to 1. The closer its value to one, the greater the consistency of the model results with the experiment results.

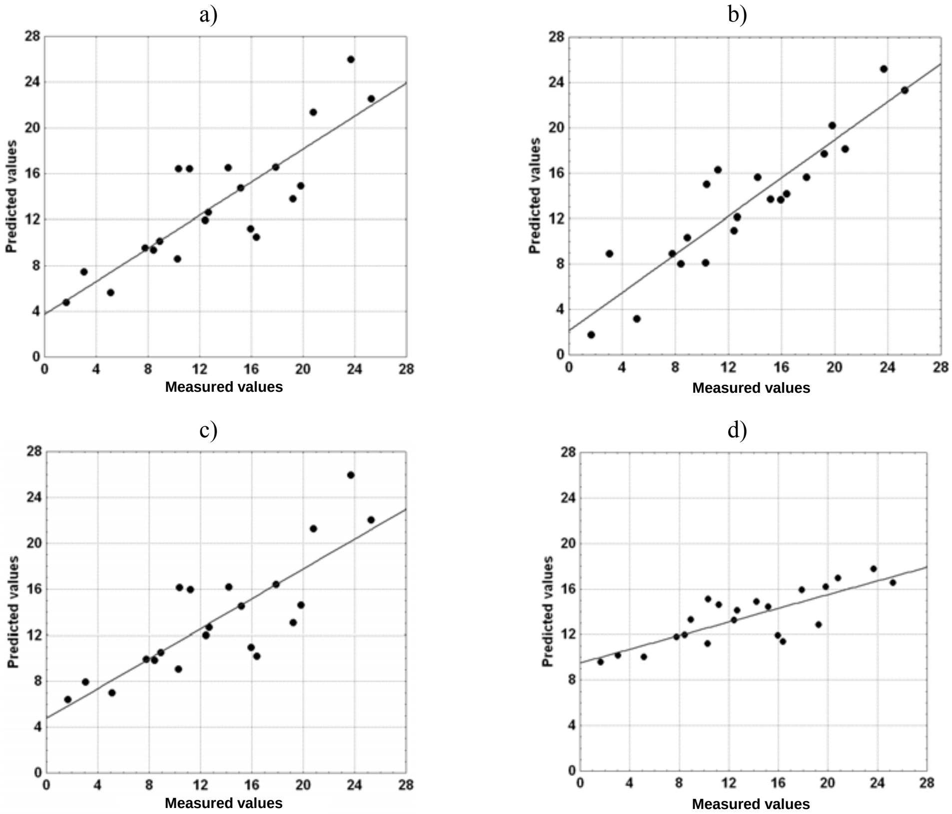

Fig. 2. Diagrams of measured versus predicted values for the relation between Tb.Th–BMD and σ_c for coxarthrotic samples, with the use of: a) multiple regression, b) response surface regression, c) authors' own model I, d) authors' own model II

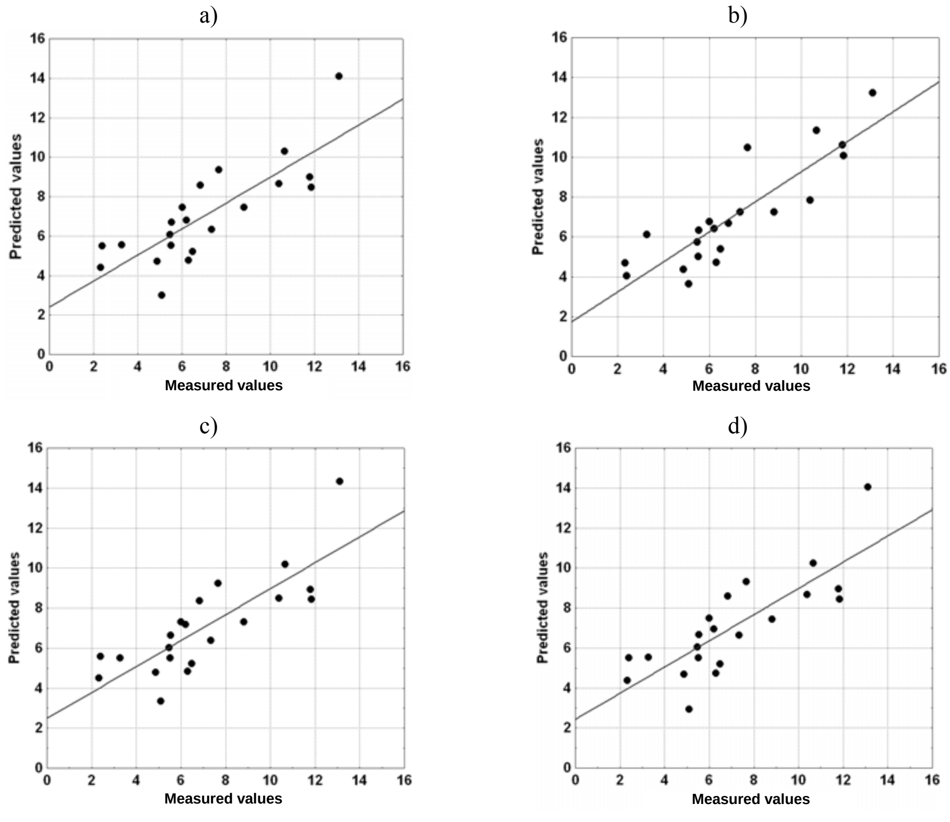

Fig. 3. Diagrams of measured versus predicted values for the relation between BV/TV–BMD and σ_c for osteoporotic samples, with the use of: a) multiple regression, b) response surface regression, c) authors' own model I, d) authors' own model II

For the purpose of assessing the consistency of the model values with the experimental results, the value of *E* for all types regression was calculated which allowed us to check which of the regression model provides the best results for a given combination of variables. The highest values of the coefficient *E* are gathered in table 5.

Table 5. The highest values of coefficient *E* in both groups of samples

Parameters v_1, v_2	Coefficient *E*			
	Multiple regression	Response surface regression	Authors' own model I	Authors' own model II
Osteoporosis				
BV/TV–BMD	0.78	0.84	0.78	0.78
Tb.SP–BMD	0.78	0.83	0.77	0.78
Tb.N–BMD	0.78	0.82	0.77	0.77
Average	**0.78**	**0.83**	**0.77**	**0.78**
Coxarthrosis				
Tb.Th–BMD	0.82	0.90	0.78	0.60
BS/BV–BMD	0.83	0.89	0.78	0.64
BV/TV–BMD	0.80	0.85	0.77	0.77
Average	**0.82**	**0.88**	**0.78**	**0.67**

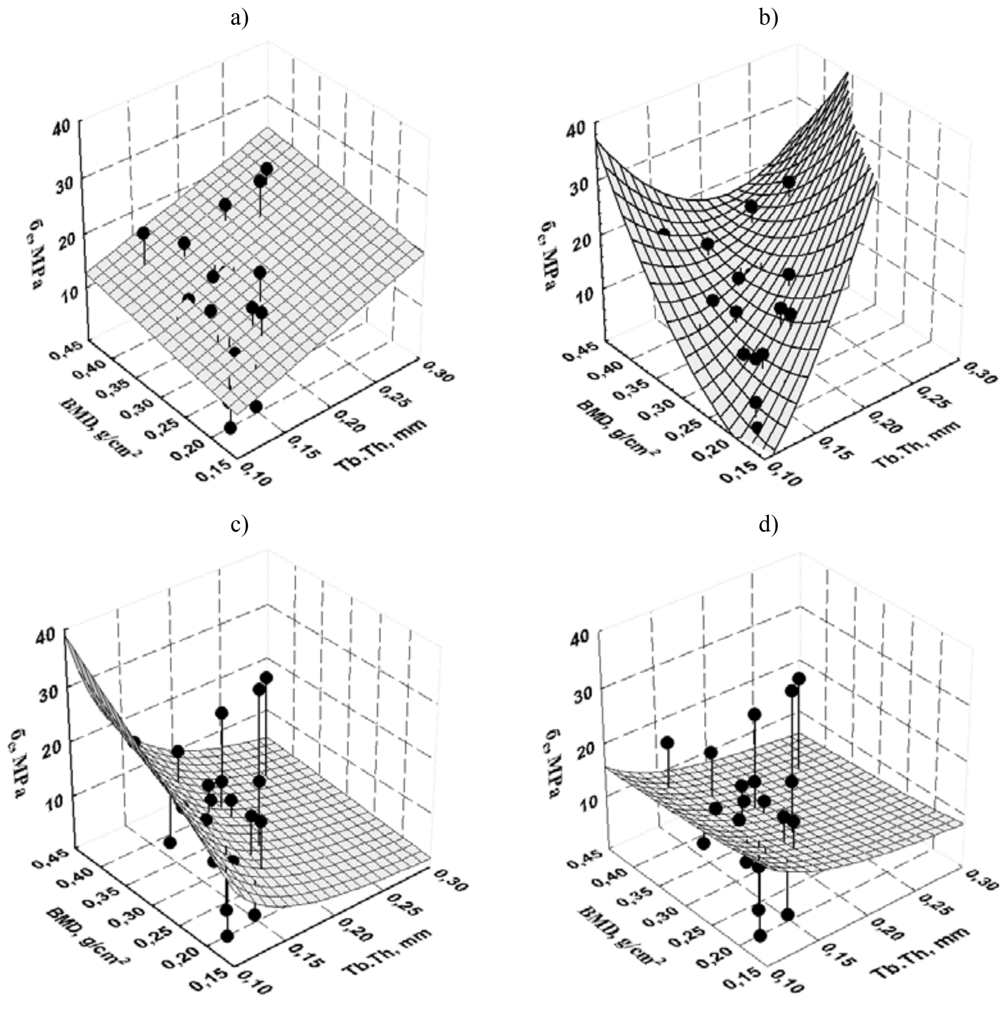

Fig. 4. 3D diagrams of the relationship between Tb.Th–BMD and σ_c for coxarthrotic samples, with the use of: a) multiple regression, b) response surface regression, c) authors' own model I, d) authors' own model II

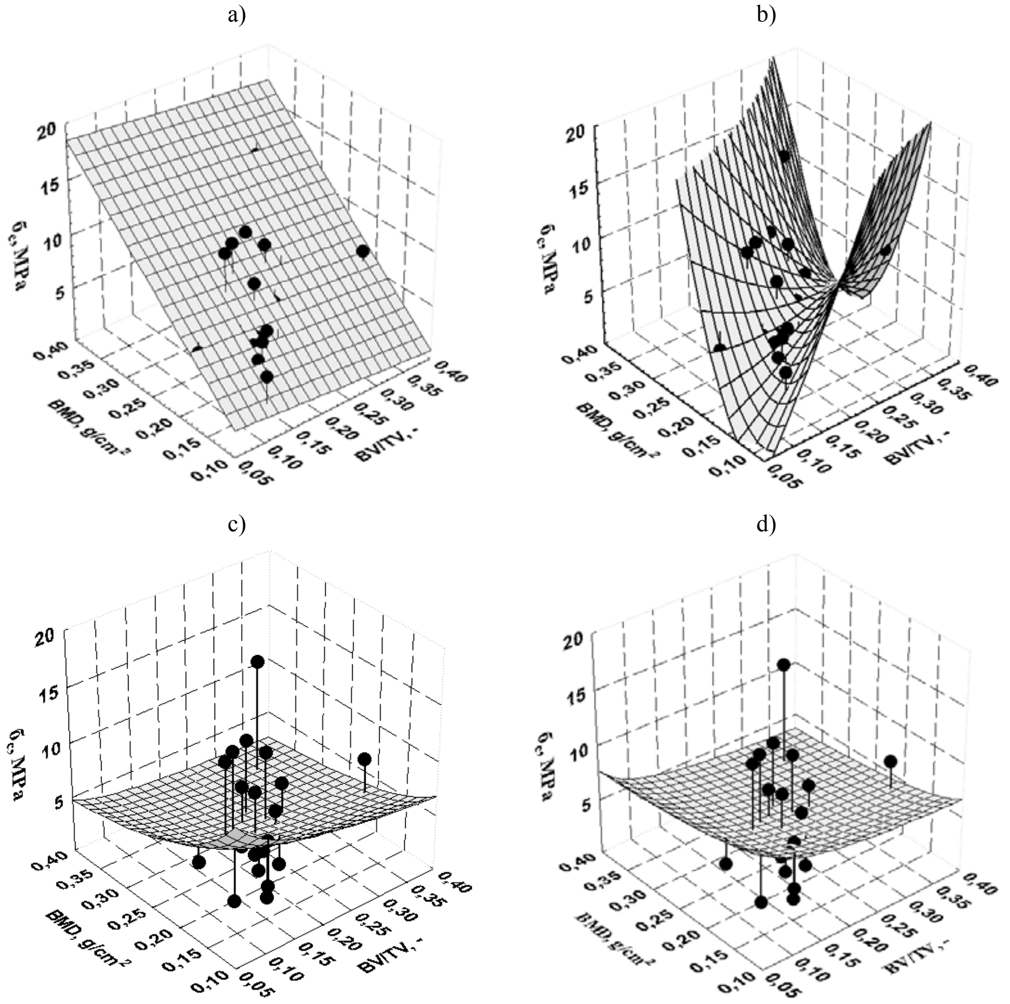

Fig. 5. 3D diagrams of the relationship between BV/TV–BMD and σ_c for osteoporotic samples, with the use of: a) multiple regression, b) response surface regression, c) authors' own model I, d) authors' own model II

3D diagrams (figures 4 and 5) show Tb.Th–BMD versus σ_c for coxarthrotic samples and BV/TV–BMD versus σ_c for osteoporotic samples (the same pairs as in figures 2 and 3).

4. Discussion

Based on the values of *R* coefficient obtained for both examined groups of samples (table 3) it can be inferrred that none of the structure parameters examined used alone is better in the strength description than BMD density. Only in one case the value *R* was better than the dependence of BMD on strength, but only in one group of samples. This allows the conclusion that the parameters of the structure examined do not provide a possibility of a better bone strength description compared with BMD density.

In the case of the regression of two variables, the values of the coefficient *R* increased in the range of 7÷30% compared with the strength estimated only on the basis of BMD density. The results obtained confirmed the assumption that the combination of BMD and the structure parameters better described the strength of bone than each parameter separately.

It can also be seen that the highest values of *R* for both types of regression were reached in particular cases in both sample groups for almost the same pairs of variables.

Having analyzed two variables of the regression models one can conclude on the basis of the value of *E* that the greatest consistence of the model with the experiment was achieved for response surface regression, and then for multiple regression. As a result of calculations according to our own models of regression no greater consistency of the calculations with the experimental results was obtained.

The tests were carried out on a relatively small number of samples. For this reason the calculations of the relationships with density combinations and more than two parameters have not been considered. The relationships between the combinations of two different structure parameters and strength have not been taken into account, either. Therefore, in order to confirm the validity of the results obtained, the above mentioned tests should be conducted on a greater number of samples.

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