Acta of Bioengineering and Biomechanics
Vol. 14, No. 2, 2012

Original paper
DOI: 10.5277/abb120205

Correlations between structural and mechanical properties of human trabecular femur bone

ANNA NIKODEM*

Division of Biomedical Engineering and Experimental Mechanics, Wrocław University of Technology, Wrocław, Poland.

In this article, the author presents mathematical relationships between the structural and mechanical properties of cancellous human bone tissue obtained by experimental analysis of specimens. Bone tissue material can adjust its internal structure to the existing loading conditions. The mechanical properties affect the structural properties but changes in structural properties likewise cause changes in the mechanical properties of the tissue. In normal tissue, the processes of tissue construction, destruction, and reconstruction are mutually balanced and complementary; if that balance is disturbed, lesions can occur. Therefore, normal bone tissue and pathologically changed tissue (osteoporosis and osteoarthrosis) coming from the area of human femoral head were examined. The structural properties of cancellous tissue specimens were determined non-destructively for three-dimensional reconstructions with the use of modern micro-CT methods. The mechanical properties of the specimens were determined by an uniaxial compression test in three orthogonal directions. Next, in order to specify the compressive strength, a failure test was conducted in the direction perpendicular to the neck–shaft angle of the hip joint.

Key words: *osteoporosis, osteoarthritis, mechanical properties, microtomography*

1. Introduction

The operation of the highly complex structure such as the human skeletal system is possible thanks to an appropriate construction and the properties of bone tissue. Sufficient strength for maintaining minimum mass, necessary resilience, and the ability to transfer loads can only be ensured by the optimum connection of various bone tissue components, whose features are mutually complementary. From the viewpoint of mechanics, bone is the most amazing "material" known to science because in the case of changing conditions it has the ability to adapt to them in order to optimally perform its functions. As early as in the 19th century, Wolff noticed that an internal structure of bone tissue adapts to the existing loading conditions. Adaptive changes, caused by gradual bone adaptation to the changing loads, are therefore connected with both structural and mechanical properties of bone tissue (KABEL et al. [15]).

A balance disturbance (overload) caused by the processes of functional adaptation of bones, additionally amplified by such factors as age and bone quality, may result in bone tissue pathologies. An understanding of pathological mechanisms causing lesions and the methods of their diagnosis and therapy still constitute one of the most important problems of contemporary medicine. In many cases, the outcome of the conducted treatment depends strictly on the assessment of the mechanical properties of bone tissue and internal tissue structure; in such cases, improvement in the outcome is strictly related to the possibilities of describing the mechanical properties of bone tissue. Consequently, an understanding of the relationships between the tissue structure and its mechanics will enable not only an improvements in bone tissue diagnostics and therapy, but also determination of the

* Corresponding author: Anna Nikodem, Division of Biomedical Engineering and Experimental Mechanics, Wrocław University of Technology, ul. Łukasiewicza 7/9, Wrocław, Poland. Tel.: +48 71 320 20 83, fax.: +48 71 322 76 45, e-mail: anna.nikodem@pwr.wroc.pl

Received: March 26th, 2012
Accepted for publication: May 7th, 2012

mechanisms by which normal bone tissue changes into pathological one. Therefore, one of the most important topics undertaken in modern literature on bone tissue description is the search for correlations between the mechanical and structural tissue properties (GOULET et al. [11], HUISKES [14], CICHAŃSKI et al. [6]).

Numerous works analysing mechanical properties of bone tissue (EVANS [9], YAMADA [30], BAYRAKTAR et al. [2], COWIN [7]) show that for a bone which is a strongly anisotropic material no simple relationships can be determined which describe its character. The reason for that is that the values of mechanical parameters depend on numerous factors, among which the most important seems to be the structure of the object examined. Cancellous bone tissue constitutes a three-dimensional network of bone trabeculae having different shapes, dimensions, and orientation (AN and DRAUGHN [1]). The term "cancellous bone tissue structure" means here the method of organisation of the basic tissue-forming elements.

Taking into account the undertaken direction of studies, the works describing structural parameters of the cancellous bone tissue can be divided into three groups. The first group is concerned with the description of the methods and techniques of bone tissue imaging (WHITEHOUSE [29]). The second group deals with search for parameters which would quantify bone tissue structure (ODGAARD [23], HILDEBRAND et al. [12]). The third group consists of works whose purpose is to determine the relationships between individual structural parameters. The subject matter of the works in the first group is complementary to that of the second one. The desire to obtain information on the morphological parameters of bone tissue created a need to develop special methods for observing and measuring cancellous bone tissue (CARBONARE et al. [5]). Measurements of the structural properties are based on stereological and topographic methods used to quantify bone tissue histology (FELDKAMP et al. [10], HILDEBRAND et al. [13]). Such information concerns both parameters describing size and shape of the objects tested and parameters describing their orientation (structural anisotropy).

Density is the structural parameter most often correlated with the mechanical properties of bone tissue (RICE et al. [25], COWIN and CARDOSO [8]). Although the studies conducted to describe correlations between mechanical parameters and bone density show that the specimens analysed are characterised by similar values of mineral density, their mechanical parameters may have different values (TANAKA et al. [26]). Consequently, density alone is not a sufficient to describe discrepancies in the obtained values of the mechanical parameters. Those results support the argument that mechanical properties of bone tissue depend not only on tissue density, but also on structural parameters which determine the organisation of bone tissue in the specimen tested. Therefore, the properties of the whole examined bone tissue structure depend on the properties of the individual bone trabeculae as well as on the way and the number of their interconnections. The description of the structural properties is based on a whole range of parameters defining mass distribution in a bone tissue specimen, orientation of the structure, and its character (PARFITT et al. [24]). The constantly growing number of new parameters used for the description points to a lack of the satisfying description of the structural properties.

Adaptive changes of bone tissue as a result of bone adaptation to the existing loads under conditions of balance disturbance (overload), together with additional factors such as age or bone quality, may lead to irreversible changes in a bone, including fracture. This also happens in the case of osteoporosis, also known as "brittle bone disease". Osteoporosis is a chronic, metabolic disease of the skeleton, characterised by reduced amount of bone mass, disturbed bone microarchitecture, and, consequently, lowered mechanical resistance to loads and traumas, which ultimately leads to an increased risk of fractures (BURR et al. [4], NAZARIAN et al. [20]). A bone fracture typically occurs in a fall, when the force of trauma is greater than the bone strength. Complications and mortality following femur bone fracture increase with age. Apart from osteoporosis, the second most common indication for hip joint replacement is osteoarthrosis, i.e., bone tissue degeneration. That disease causes destruction and loss of articular cartilage and exaggerated growth (hypertrophy) of bone tissue in the periarticular area, which changes mechanical conditions in the joint area (KEUTTNER and GOLDERG [17], BUCKWALTER et al. [3], NIKODEM and ŚCIGAŁA [21]). Its origin is not completely understood.

In the literature, attempts to describe correlations between the structural and mechanical properties of bone tissue most often rely on the studies of "normal" bone tissue (GOULET et al. [11]). Pathological changes seen in the clinical picture indicate that the two diseases differ a lot from each other and from normal tissue as to their structures, so they should also exhibit different mechanical properties. Consequently, the description of those properties is important for an understanding of the mechanisms of the initiation of bone tissue changes.

Therefore, the main purpose of the studies conducted is to determine the structural and mechanical properties of bone tissue, to search for correlations between them, and to attempt to describe such correlations by means of mathematical relationships. Those correlations have been determined for normal and pathologically changed bone tissue.

2. Materials and methods

2.1. Bone specimens

The subject of the studies was the proximal epiphysis of the human femur bone. The material consisted of 89 specimens of bone tissue coming from 3 separate groups. The first group was the control group (F) consisting of 4 epiphyses of normal femur bone without lesions, obtained post mortem. The second group of specimens consisted of 7 femoral heads of patients diagnosed with osteoporosis (OP). The third group consisted of 12 femoral heads diagnosed as cases of osteoarthrosis (OA). The material of the second and third group was biological material coming from patients qualified for hip joint replacement. Donor age ranged from 42 to 79 years, with a mean age of 63 ± 10 years. Before the tests each of the test preparations was stored at a temperature of –20 °C in a double plastic packaging. Due to the scope of the measurements conducted, the tests were split into 4 stages according to the algorithm presented in figure 1. The first stage of the research was the analysis of the radiological density of bone tissue in order to determine the degree of bone tissue changes in disease processes and to identify the locations from which bone specimens were then prepared for further test stages.

Bone specimens were prepared in order to determine both structural and mechanical properties of cancellous bone tissue. Due to the nature of the measurements conducted (elastic mechanical properties were determined in three orthogonal directions), 4 cubic specimens were prepared from each head (10 mm × 10 mm × 10 mm). The specimens were cut out at a speed of 1 mm/s using Accutom–5, STRUERS® automatic precision cutter.

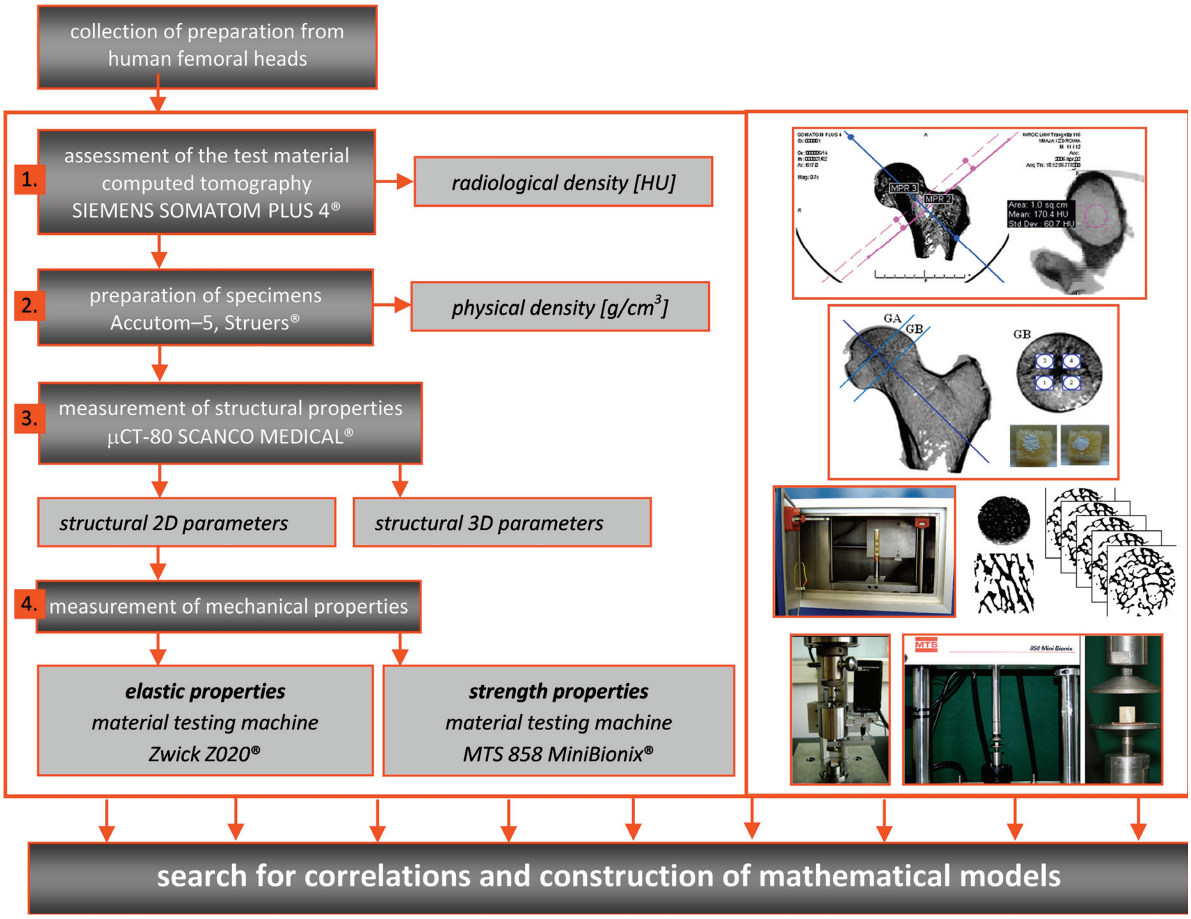

Fig. 1. Algorithm of work measurements carried out in order to determine the mechanical and structural properties of bone tissue and to find models describing their interrelations

2.2. Specimen preparation

In order to specify structural properties for each of the specimens, an analysis was conducted of the cancellous bone tissue specimens using X-ray microtomography (μCT-80, Scanco Medical®, Switzerland). CT images were acquired at 20 μm voxel size 70 kV, 114 μA. CT system provides a series of cross-sections along the axis perpendicular to the neck–shaft angle of the femoral bone, at an image resolution of 512 × 512. Next, using the μCT system software, average values of morphometric parameters were determined as well as three-dimensional values of structural parameters (through a reconstruction of plane sections). The analysis covered both classic morphometric parameters (Tb.N, Th.Th, and other) as well as parameters involving special organisation of bone tissue, such as: connectivity density ConnD and the DA index, which describe anisotropy of the structure. The quantitative description of structural anisotropy used the MIL method to determine the fabric ellipsoid parameters (WHITEHOUSE [29]) and the DA parameter. Additionally, 3D reconstruction enabled determination of the SMI value for each specimen, providing information about the character of bone tissue (HILDEBRAND et al. [13], ODGAARD [23]) as well as mineral content of the tissue, defined as the reference value to the phantom value, expressed in mg HA/cm^3, with respect to the phantom built into μCT, of a determined density.

2.3. Biomechanical testing

In order to determine the mechanical properties of bone tissue, each of the bone tissue specimens was subjected to two-stage tests of uniaxial compression. During the first stage, the elastic properties of bone tissue cubic specimens were determined in three orthogonal directions. In order to avoid edge effects related to defragmentation of ends of bone trabeculae, and thus the possibility of sliding the elements compressed between the grips, sandpaper was additionally used with the grain thickness of 80. The specimens subjected to measurements of elastic properties were initially loaded to the value of 3 N, and then, at a strain rate of 0.01/s, were loaded to the value of 1% of specimen deformation. During the final stage the specimens were subjected to stress tests in the direction No. 1 (along the axis of the neck–shaft angle). In both measurements, the rate of deformation equalled 0.01/s, which corresponds to deformations under physiological conditions. The tests were carried out with the use of universal material testing machines Zwick Z020 and MTS 858 MiniBionix.

2.4. Statistics

Statistical analysis included: basic statistical characteristics, verification of normal distribution in the specimen (the Shapiro–Wilk test), the ANOVA monofactorial and multifactorial analysis, and the multiple regression analysis conducted with the use of the Origin 7.0 program.

3. Results

In order to determine the structural properties of bone tissue experiencing various conditions (normal,

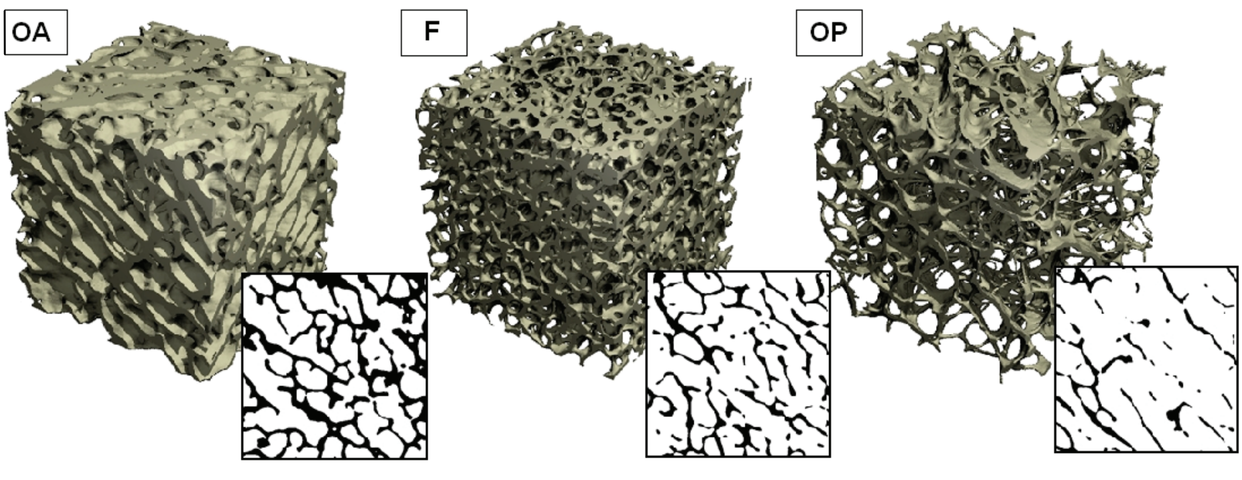

Fig. 2. Sample 3D reconstructions of specimens: osteoarthritic OA, control group F, and osteoporotic OP, obtained by means of μCT-80, Scanco Medical®, Switzerland

osteoporotic, and osteoarthritic tissues), the studies were conducted with the use of X-ray microtomography, which enabled 3D reconstructions of each of the specimens prepared for tests. Sample photographs for each of the measuring groups can be found in figure 2.

3.1. Structural properties

The qualitative and quantitative analyses show that each of the groups studied (OA, F, and OP) differs in the number and type of the respective trabeculae, their connections, and the way of their organisation in the specimen tested. The specimens prepared from osteoporotic bone (OP) are characterised by the smallest BV/TV density compared to the other groups, in the range from 9 to 30%, while at the same time they have the highest values of the BS/BV parameter. Additionally, the OP specimens have the smallest values of Tb.N and Tb.Th parameters. Unlike osteoporotic OP specimens, the osteoarthritic OA specimens are characterised by concentration of bone material and have the highest BV/TV values (by 5% compared to the control group and by 40% compared to the OP group). This trend also persists in the case of such parameters as Tb.Th and Tb.Sp. All values of the structural parameters describing geometry of the control group specimen are located in between, separating the OP and OA values (table 1).

A change of geometry of the individual specimens in the groups tested is also associated with a change of the structural anisotropy. Compared to the control group specimens, the osteoporotic tissue is characterised by increased anisotropy (DA), whereas the osteoarthritic tissues is characterised by decreased anisotropy (figure 3 and table 1).

Similar parallels can also be found in the third group of structural parameters, defining its organisation and character of the tissue. The number of tra-

Table 1. Values of the structural parameters describing geometry for each of the groups tested

Variable		Physiology (F)		Osteoarthritis (OA)		Osteoporosis (OP)	
Structural properties	Unit	Value	±*SD*	Value	±*SD*	Value	±SD
Bone volume /total volume (BV/TV)	%	25.32	5.67	26.71	6.83	18.86	5.00
Bone surface/bone volume (BS/BV)	1/mm	13.38	1.97	12.99	2.64	15.96	2.97
Trabecular number (Tb.N)	1/mm	1.42	0.15	1.47	0.21	1.32	0.18
Trabecular thickness (Tb.Th)	mm	0.18	0.02	0.20	0.04	0.17	0.03
Trabecular spacing (Tb.Sp)	mm	0.67	0.08	0.64	0.09	0.72	0.11
Degree of structural anisotropy (DA)	1	1.59	0.15	1.62	0.20	1.71	0.26

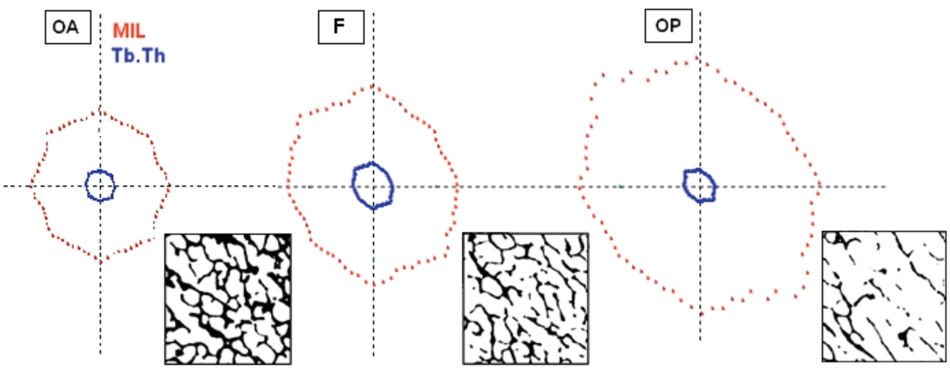

Fig. 3. Fabric elipsa as well as the MIL and Tb.Th values for specimens of the osteoarthritic tissue OA, the control group F, and the osteoporotic tissue OP, obtained by means of μCT

Table 2. Values of the structural parameters describing anisotropy and mineral density for each of the groups tested

Variable		Physiology (F)		Osteoarthritis (OA)		Osteoporosis (OP)	
Structural properties	Unit	Value	±*SD*	Value	±*SD*	Value	±*SD*
Connectivity density (ConnD)	$1/mm^3$	6.49	2.25	6.08	3.28	5.02	1.38
Structure model index (SMI)	1	1.12	0.08	1.21	0.09	1.10	0.43
Mineral density (rminer)	mg HA/cm^2	211.99	73.43	207.60	75.31	116.72	62.96

beculae and the number of connections between individual trabeculae decrease both for OA and OP specimens compared to the control group specimens. However, there is only a small decrease in the case of OA specimens (by 6%) in contrast to the rapid drop in the case of OP specimens (by 24%). The value of the ConnD parameter, describing the degree of connections of a given structure, equals 5.02 (1/mm^3) for osteoporotic cancellous tissue (OP), which means a drop compared to the physiological tissue specimens by approx. 28%, whereas the ConnD value for osteoarthritic specimens equals 6.08 (1/mm^3), which means a drop by 14%. The character of the tissue also changes somewhat, as signalled by the SMI parameter. The value of the SMI parameter for osteoarthritic specimens falls within the range of (0.1–1.86), which is characteristic of bar specimens, whereas SMI for osteoarthritic specimens (OA) falls within the range of (–1.12–0.79), which is characteristic of mixed-type specimens with predominantly plate elements.

The ANOVA statistical analysis demonstrated a difference of $p < 0.05$ in the OP group compared to the remaining groups in the BV/TV andTb.Th values and differences between all groups in the Tb.N and Tb.Sp values. Additionally, there is a statistically significant difference in the BS/BV values ($p < 0.05$) of the F a OP groups and in the DA values of the OA a OP groups. In the case of DA and ConnD parameters, the ANOVA analysis did not show any statistically significant difference in the results obtained; in the case of the SMI parameter, the analysis demonstrated that the specimens of the OP and OA groups differ significantly at a level of $p < 0.05$, and in the case of the mineral density parameter that difference concerns the groups OP and OA as well as OP and F.

3.2. Mechanical properties

For each of the specimens mechanical properties such as elasticity and strength were measured by means of a uniaxial compression test, using universal material testing machines Zwick Z020 and MTS 858 MiniBionix. The results obtained are presented in table 3. Compared to specimens of pathologically changed tissues, normal bone tissue is characterised by the highest values of elasticity parameters (Young's modulus in three orthogonal directions) as well as strength parameters. Comparing the respective values of Young's modulus for the same specimen, obtained in three orthogonal directions, the smallest differences were observed in specimens of the control group (the DM parameter). As in the case of the coefficient describing structural anisotropy, the mechanical anisotropy coefficient changes together with the group tested. Here, it increased compared to the control group (in the case of specimens of the OA group by 4% and in the case of the OP group by 9%). Therefore, the results obtained show that a change of structural parameter values in various directions (repre-

Table 3. Values of the mechanical parameters for each of the groups tested

Variable		Physiology (F)		Osteoarthritis (OA)		Osteoporosis (OP)	
Mechanical properties	Unit	Value	±*SD*	Value	±*SD*	value	±*SD*
Modulus of elasticity (E_1)	MPa	147.41	67.60	143.15	81.38	72.33	68.68
Modulus of elasticity (E_2)	MPa	157.36	118.81	89.32	47.15	45.29	32.71
Modulus of elasticity (E_3)	MPa	174.26	131.96	95.48	62.63	50.32	32.31
Yield strength (σ_{ult})	MPa	11.36	3.96	12.68	6.97	7.88	4.12
Stain energy (U)	mJ/mm^2	30.98	2.15	27.92	1.79	15.25	1.78

Table 4. The Pearson product-moment correlation coefficients R among individual structural parameters, $p < 0.001$

	BV/TV	Tb.Sp	DA	ConnD	Ln(ConnD)	SMI	ρ_{miner}
BV/TV	1	–0.51	–0.29	0.66	0.68	–0.82	0.97
Tb.N	0.77	–0.96	–0.23	0.67	0.77	–0.48	0.74
Th.Th	0.81	–0.50	–0.45	0.27	0.34	–0.69	0.82
Tb.Sp		1	0.15	–0.64	–0.76	0.32	–0.64
DA			1	–0.14	–0.14	0.33	–0.41
ConnD				1	1	–0.39	0.54
SMI						1	–0.82
ρ_{miner}							1

sented by the DA parameter) has a smaller impact on an increase in the mechanical anisotropy DM of the specimen tested. An increase in structural anisotropy by 24% is connected, among other, with a reduced number of horizontal trabeculae, and thus the number of connections between the respective trabeculae observed for OP tissue specimens. The above increase causes a growth of just 9% in their mechanical anisotropy (table 3).

In order to determine the relationships between the structural and mechanical properties of bone tissue, it was first necessary to specify how the various parameters were interrelated. The knowledge of those correlations will enable selection of parameters which significantly depend on each other, which in turn will reduce the number of variables having direct impact on the mechanical properties. Therefore, in the next stage of the analysis conducted, the strength of correlations between the respective structural properties (table 4) as well as structural and mechanical properties, determined in experimental studies, were established. The values presented in detail in table 3 are the structural properties obtained for a three-dimensional reconstructed specimen (structural 3D parameters) coming directly from studies using μCT.

A very important aspect, from the viewpoint of building relations, is their physical significance. The value of the coefficient of correlation between Tb.N and Tb.Th amounts to just $R = 0.35$. From the physical point of view, the number of bone trabeculae does not depend on their thickness unless the thickness reaches such a value that the individual trabeculae will "stick" together. Since there are relationships between the respective structural characteristics, in the latter stages of constructing mathematical relationships between the structural and mechanical properties the most important are dependent parameters, including: Tb.Sp, BV/TV, ConnD, and SMI. Using a multiple analysis, which allows us to examine the dependence of one variable on a few, we can find the following relationships:

$$\mathrm{SMI} = f(\mathrm{BV/TV}, \rho_{\mathrm{miner}}), \quad (1)$$

$$\mathrm{ConnD} = f(\mathrm{Tb.N}, \mathrm{Tb.Sp}). \quad (2)$$

On the basis of the results obtained we can conclude that the best correlations for Young's modulus were obtained with the BV/TV value. Considering the fact that bone tissue is a strongly anisotropic structure, the mechanical properties of the specimen will also depend on individual properties of bone trabeculae lying in the loading direction. After taking into account all of the above-mentioned parameters, the multiple regression analysis provided the relationships (3), (4). The volume content (BV/TV) depends on the number of trabeculae and their thickness. Consequently, the elastic properties of bone tissue depend on the BV/TV values, the number of bone trabeculae, the thickness, and the character of bone trabeculae (the SMI parameter).

$$E = f(\mathrm{BV/TV}, \mathrm{SMI}, \rho_{\mathrm{miner}}), \quad (3)$$

$$\sigma_{\mathrm{ult}} = f(\mathrm{BV/TV}, \mathrm{Ln(ConnD)}, \mathrm{SMI}). \quad (4)$$

Figures 4 and 5 present the values of the correlation coefficients of Young's modulus and compressive strength with structural properties, in accordance with equations (3) and (4) obtained with the use of multiple regression analysis. On the basis of the results obtained we can see that the insertion of the SMI variable in relationship (3) increases the value of the regression coefficient R by 1%. Additionally, given the fact that bone tissue elasticity may change in accordance with the degree of tissue mineralization, another increase in the coefficient R value was obtained by up to 12% (for the OP tissue). The values presented also demonstrate that changes in the values of bone tissue mineral density have a far greater impact on the modulus of elasticity than the SMI parameter.

Due to the high level of complexity of cancellous tissue, the resultant mechanical values will certainly depend on the mechanical properties of the respective bone trabeculae. In the case of compressive strength, some of the key parameters are unquestionably structural consistency and the character of the respective bone trabeculae. According to the studies conducted at other centres, a structure made of evenly placed, thick (SMI↓), not as numerous (Tb.N↓), widely spaced bone trabeculae (Tb.Sp↑) transfers greater loads

Table 5. The Pearson product-moment correlation coefficients R between the mechanical parameters E_1, E_2, E_3, σ_{ult} and the structural parameters, $p < 0.001$

	BV/TV	Tb.N	Th.Th	Tb.Sp	Ln(ConnD)	SMI	DA	ρ_{miner}
E_1	0.61	0.37	0.59	–0.29	0.32	–0.63	–0.38	0.77
E_2	0.67	0.34	0.63	–0.23	0.34	–0.72	–0.37	0.74
E_3	0.46	0.34	0.33	–0.28	0.34	–0.44	–0.34	0.61
σ_{ult}	0.85	0.75	0.62	–0.64	0.75	–0.68	0.12	0.83

($\sigma_{ult}\uparrow$) than a structure made of a greater number of thinner bone trabeculae that are also widely spaced (KLEEREKOPER [18]).

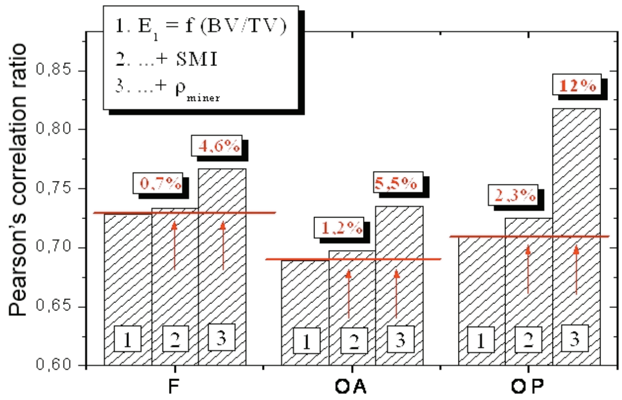

Fig. 4. Values of Young's modulus between the parameter E_1 and structural parameters in accordance with equation (3), obtained as a result of multiple regression analysis; $p < 0.0001$

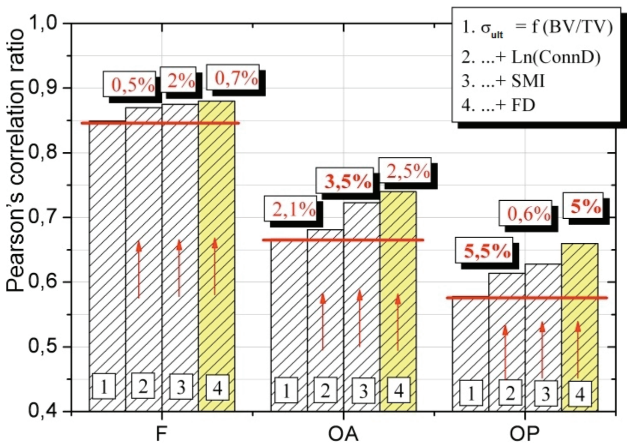

Fig. 5. Values of Young's modulus between the parameter σ_{ult} and structural parameters in accordance with equation (4), obtained as a result of multiple regression analysis; $p < 0.0001$

Table 6. Values and ranges of the parameters determining structural anisotropy (DA) and mechanical anisotropy (DM), $p < 0.0001$

Variable	Physiology (F)	Osteoarthritis (OA)	Osteoporosis (OP)
DA	1.59 ± 0.15	1.62 ± 0.20	1.71 ± 0.26
DM	1.94 ± 0.42	2.02 ± 0.48	2.19 ± 0.86
DA/DM	0.689	0.678	0.657

As already mentioned, cancellous bone tissue is very highly anisotropic due to its structure as well as mechanical properties. The DA parameter determines the degree of structural anisotropy, whereas the DM parameter determines the degree of mechanical anisotropy. Therefore, assuming that mechanical tissue properties are strongly related to the mechanical properties, those parameters should exhibit a strong correlation. However, the results obtained show no strong correlations between the DA parameter and the other structural parameters and, moreover, although changes in the anisotropic values of the respective measuring groups have a similar character, no strong correlation is found between the structural and mechanical anisotropies. In table 6, the values and ranges of the parameters determining structural anisotropy (DA) and mechanical anisotropy (DM), $p < 0.0001$, are presented for normal and pathologically changed bone tissue. According to the results, a decrease by 4% in the values of structural anisotropy of the OA specimens, compared to F, causes a proportional, i.e., a 5% decrease in the values of structural anisotropy. In the case of OP tissue specimens, a 4% increase in the values of structural anisotropy causes a 20% increase in the values of mechanical anisotropy. The value of the correlation coefficient of the structural and mechanical anisotropies is the greatest for physiological specimens. This is due to the smallest scope of changes of the two values in that group and significant diversity of the specimens of pathologically changed tissues.

4. Discussion

In the article, we present the resultant values of structural and mechanical parameters determined experimentally for normal and pathological bone tissues. Therefore, we can observe that the values of structural and mechanical parameters vary widely with respect to different conditions of tissue (normal bone tissue F, osteoporotic bone tissue OP, and osteoarthritic bone tissue OA). Osteoporosis, which in the clinical picture (on X-rays) is manifested by a significant dilution of bone tissue, is characterised by the lowest value of density and volume content (BV/TV) compared to the other cases. Additionally, the results show that osteoporotic tissue from the femoral head is built of bone trabeculae of a mixed character, with a significant predominance of bar elements. Also, the analysis of mechanical properties of bone tissue shows that such tissue is characterised by the smallest value of mechanical parameters and the highest value of anisotropy, both structural DA and mechanical DM. As demonstrated by the literature, the changes connected with osteoporosis are caused by the loss of tissue cohesion, resulting from thinning individual bone trabeculae or their total loss. Such a decrease in bone trabeculae thickness is connected with an excessive resorption of bone tissue. Studies found a 20% decrease in the Tb.Th values and a sharp 40% drop in the number of trabeculae (Tb.N).

The studies carried out for osteoarthritic bone tissue OA prove that cancellous bone tissue is characterised by a significant concentration of bone material, particularly in the region of subchondral tissue. The specimens of OA tissue are made of bone trabeculae with negative SMI coefficient and characterised by very dense structures such as a uniform cube filled with spherical pores. Changes in tissue structure, taking place in osteoarthrosis, are caused by a loss of articular cartilage, which causes changes in the hip joint mechanics. Loss of articular cartilage leads to increased friction forces between the hip joint elements, and consequently to irreversible bone deformations. The rebuilding of bone tissue causing its hypertrophy, particularly in the area of subchondral layer, resulted in increased mechanical resistance, thus changing the character of the tissue to more fragile (*U* parameter).

When examining the results, we should be aware that this study has some limitations which concern especially the amount of material and some errors generated by mechanical test (WEINANS et al. [28], KEAVENY et al. [16], NIKODEM and ŚCIGAŁA [22]). At the boundary where a specimen is in contact with the loading platen (in our case to eliminate misalignment errors we use a pivoting platen) the trabeculae can be exposed to bending (TURNER and BURR [27]). That is why we use small cubes of bone, which was compressed with abrasive paper, to eliminate those end effects. However, it is still necessary to collect the study with more material from various patients with different stage of bone diseases and different age.

The paper also presents the correlations between the respective structural parameters describing geometry, anisotropy, and the character of cancellous tissue architecture. Similar studies conducted by GOULET [11] show high correlations (of the order of 90%) between the number of trabeculae (Tb.N), bone volume fraction (BV/TV), and connectivity (ConnD), even though those parameters are not interconnected by the existing mathematical relationships (LINDE et al. [19]). In their studies, GOULET et al. [11] also analysed the correlations between individual structural and mechanical properties; however, they only carried out studies for normal tissue (without pathologies) for which they managed to obtain a high correlation coefficient between strength and BV/TV and Tb.Th.

To sum up, strong correlations were found between the respective structural properties of specimens in each measuring group tested, but due to lack of strong correlations between those parameters and the mechanical properties an analysis was conducted with the use of multiple regression. Thanks to the multifactorial analysis we were finally able to obtain a high correlation coefficient between the structural and mechanical properties. The mathematical relationships proposed that way are characterised by a high correlation coefficient of the order of 80–90% which means that on the basis of just structural properties of bone tissue we can determine with high probability its mechanical properties both for normal tissue and pathological cases.

Acknowledgements

The author would like to thank Bert van Rietbergen, Eindhoven University of Technology, for his help and access to micro-CT system. This research would not have been possible without help from Professor Szymon Dragan, Clinical Department of Orthopaedic and Traumatologic Surgery, Wrocław Medical University, who provided the clinical material used.

This work has been supported by the National Science Centre No. N N518 505139.

References

[1] AN Y.H., DRAUGHN R.A., *Mechanical testing of bone and bone–implant interface*, CRC Press LLC, 2000.

[2] BAYRAKTAR H.H., MORGAN E.F., NIEBUR G.L., MORRIS G.E., WONG E.K., KEAVENY T.M., *Comparison of the elastic and yield properties of human femoral trabecular and cortical bone tissue*, Journal of Biomechanics, 2004, 37, 27–35.

[3] BUCKWALTER J.A., MARTIN J.A., BROWN T.D., *Perspectives on chondrocyte mechanobiology and osteoarthritis*, Biorheology, 2006, 43(3–4), 603–609.

[4] BURR D., FORWOOD M., FYHRIE D., MARTIN R., SCHAFFLER M., TURNER C., *Bone microdamage and skeletal fragility in osteoporotic and stress fractures*, Journal of Bone and Mineral Research, 1997, 12, 6–15.

[5] CARBONARE L.D., VALENTI M.T., BERTOLDO F., ZANATTA M., ZENARI S., REALNI G., CASCIO V.L., GIANNINI S., *Bone microarchitecture evaluated by histomorphometry*, Mikron, 2005, 36, 609–616.

[6] CICHAŃSKI A., NOWICKI K., MAZURKIEWICZ A., TOPOLIŃSKI T., *Investigation of statistical relationships between quantities describing bone architecture, its fractal dimensions and mechanical properties*, Acta of Bioengineering and Biomechanics, 2010, 12(4), 69–77.

[7] COWIN S.C., *Bone Mechanics Handbook*, Boca Raton, FL, CRC Press, 2001.

[8] COWIN S.C., CARDOSO L., *Fabric dependence of bone ultrasound*, Acta of Bioengineering and Biomechanics, 2010, 12(2), 3–23.

[9] EVANS F.G., *Mechanical properties of bone*, Charles C. Thomas, Publisher, Springfield, Illinois, USA, 1973.

[10] FELDKAMP L.A., GOLDSTEIN S.A., PARFITT A.M., JESION G., KLEEREKOPER M., *The direct examination of three-dimensional bone architecture in vitro by computed tomography*, Journal of Bone and Mineral Research, 1989, 4, 3–11.

[11] GOULET R.W., GOLDSTEIN S.A., CIARELLI M.J., KUHN J.L., BROWN M.B., FELDKAMP L.A., *The relationship between the structural and orthogonal compressive properties of trabecular bone*, Journal of Biomechanics, 1994, 27, 375–389.

[12] HILDEBRAND T., LAIB A., MÜLLER R., DEQUEKER J., RÜEGSEGGER P., *Direct three-dimensional morphometric analysis of human cancellous bone: microstructural data from spine, femur, iliac crest and calcaneus*, Journal of Bone and Mineral Research, 1999, 14(7), 1167–1174.

[13] HILDEBRAND T., RÜEGSEGGER P., *A new method for the model independent assessment of thickness in three-dimensional images*, Journal of Microscopy, 1997, 185, 67–75.

[14] HUISKES R., *If bone is the answer, then what is the question?* Journal of Anatomy, 2000, 197, 145–156.

[15] KABEL J., ODGAARD A., van RIETBERGEN B., HUISKES R., *connectivity and the elastic properties of cancellous bone*, Bone, 1999, 24(2), 115–120.

[16] KEAVENY T.M., PINILLA T.P., CRAWFORD R.P., *Systematic and random errors in compression testing of trabecular bone*, Journal of Orthopedic Research, 1997, 15, 101.

[17] KEUTTNER K.E., GOLDERG V.M., *Osteorathritic Disorders*, American Academy of Orthopedic Surgeons, Rosemont, 1995, 95–101.

[18] KLEEREKOPER M.W., *The Bone and Mineral Manual*, Academic Press, USA, 1999.

[19] LINDE F., HVID I., MADSEN F., *The effect of specimen size and geometry on the mechanical behavior of trabecular bone*, Journal of Biomechanics, 1992, 25, 359.

[20] NAZARIAN A., von STECHOW D., ZURAKOWSKI D., MULLER R., SNYDER B.D., *Bone volume fraction explains the variation in strength and stiffness of cancellous bone affected by metastatic cancer and osteoporosis*, Calcified Tissue International, 2008, 83, 368–379.

[21] NIKODEM A., ŚCIGAŁA K., *Biomechanics of Physiological and Pathological Bone Structures, Principles of Osteoarthritis – Its Definition, Character, Derivation and Modality-Related Recognition*, Bruce M. Rothschild (ed.), 2012.

[22] NIKODEM A., ŚCIGAŁA K., *Impact of some external factors on the values of mechanical parameters determined in tests on bone tissue*, Acta of Bioengineering and Biomechanics, 2010, 12(3), 85–93.

[23] ODGAARD A., *Three dimensional methods for quantification of cancellous bone architecture*, Bone, 1997, 20, 315–328.

[24] PARFITT A.M., DREZNER M.K., GLORIEUX F.H., KANIS J.A., MALLUCHE H., MEUNIEUR P.J., OTT S.M., RECKER R.R., *Bone histomorphometry: standardization of nomenclature, symbols, and units*, Journal of Bone and Mineral Research, 1987, 2, 595–611.

[25] RICE J.C., COWIN S.C., BOWMAN J.A., *On the dependence of elasticity and strength of cancellous bone on apparent density*, Journal of Biomechanics, 1988, 22, 155–168.

[26] TANAKA T., SAKURAI T., KASHIMA I., *Structuring of parameters for assessing vertebral bone strength by star volume analysis using a morphological filter*, Journal of Bone and Mineral Metabolism, 2001, 19, 150–158.

[27] TURNER C.H., BURR D.B., *Basic biomechanical measurements of bone: A tutorial*, Bone, 1993, 14, 595–608.

[28] WEINANS H., HUISKES R., GROOTENBOER H.J., *The behavior of adaptive bone-remodeling simulation models*, Journal of Biomechanics, 1992, 25(12), 1425–1441.

[29] WHITEHOUSE W.J., *The quantitative morphology of anisotropic trabecular bone*, Journal of Microscopy, 1974, 101, 153–168.

[30] YAMADA H., *Strength of biological materials*, Williams & Wilkins, Baltimore, MD, 1973.