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## ENGINEERING MECHANICS 2020

# Verification of the geometry of samples for the study of trabecular bone structures

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# Introduction

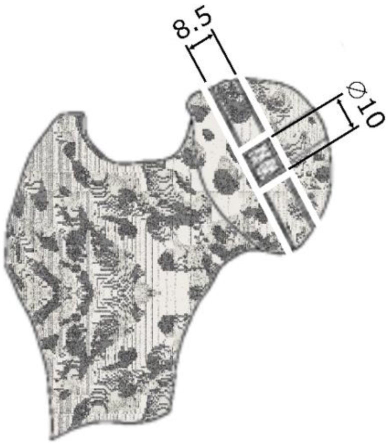
The work deals with the issue of verification of the diameter of a cylindrical sample due to the correct mapping of the mechanical properties of the trabecular bone structure during numerical analyses.

The apparent Young's modulus and the BV/TV indicator were tested in a wide range of variability of the radius of the sample of the trabecular structure.

At the stage of processing the μCT images, the best-fit cylinder algorithm was proposed to determine the geometry of the sample of the trabecular bone structure without any defects in shape and position.

# Materials

Samples of the trabecular structure taken from the neck of the human femur were examined. A set of 46 samples of structures burdened with two diseases was obtained: 15 osteoporosis and 31 coxarthrosis.




The samples were cylinders with a diameter of 10 mm and a height of 8.5 mm. After the cutting out, the samples of the trabecular structure were examined with a resolution of 36 μm on the μCT80 microtomograph. For each of the structure samples, a set of 230 images was obtained, which were then converted to binary form by thresholding, assuming the threshold value as 18% of the maximum brightness.

# Materials

The research was carried out on the basis of 5 samples selected from set n = 46 on the basis of the BV/TV indicator. Selected samples and their trabecular structure indices are presented in the Table 1.

*Tab. 1. Selected structure indicators for the analysed samples.*

| **Sample** | **Disease** | **BV/TV, -** | **Tb.Th, mm** | **TB.N, 1/mm** | **Conn.D, -** |
|---|---|---|---|---|---|
| **$P_{10}$ of BV/TV** | osteoporosis | 0.1312 | 0.1433 | 0.9485 | 0.9160 |
| **$P_{30}$ of BV/TV** | coxarthrosis | 0.1686 | 1.0183 | 0.8164 | 2.1510 |
| **$P_{60}$ of BV/TV** | osteoporosis | 0.2065 | 0.1815 | 1.1379 | 1.9552 |
| **$P_{80}$ of BV/TV** | coxarthrosis | 0.2518 | 1.3653 | 0.5480 | 4.0375 |
| **$P_{100}$ of BV/TV** | coxarthrosis | 0.3532 | 1.4967 | 0.4321 | 3.9798 |

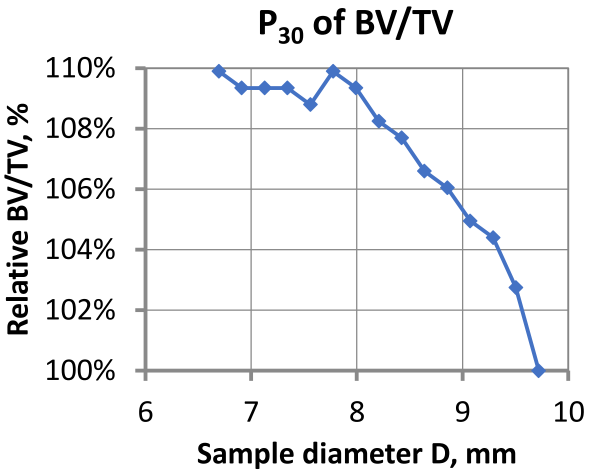
# Methods

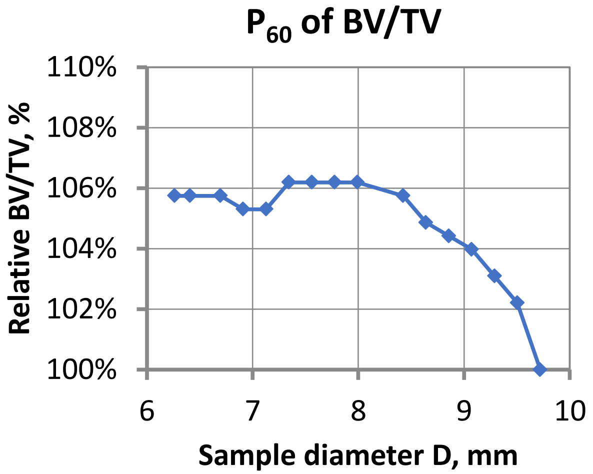
The research consisted in determining the BV/TV structure indicator and the apparent Yong modulus for cylindrical samples. The cylinders were 7.74mm long. In the course of the research, its diameter changed in the range from 9.72mm to 6.7mm in steps of 0.216mm. At erlier work it was shown that at the stage of preparing the μFE model, some μCT scans can be omitted without losing significant information about the mechanical properties of the modelled structure. However, the range of such skip should not be greater than 0.216mm.

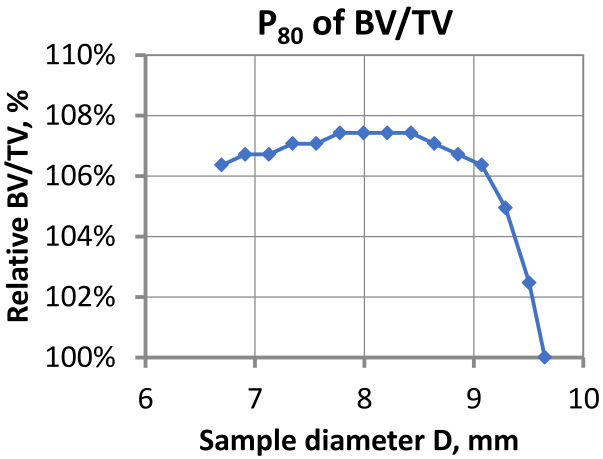
The BV/TV structure index was determined from the thresholded images by the direct method. The apparent Young's modulus was determined numerically by the finite element method in the ANSYS program environment. The mesh for the analyzes was created by directly converting voxel geometry to an element. Eight-node hexahedral elements with a size of 36 μm and isotropic material properties $E = 10GPa$ and $\nu = 0.3$ were used for the analysis. During the analyses, the cylindrical samples were compressed in the axial direction $\varepsilon=0.8\%$.

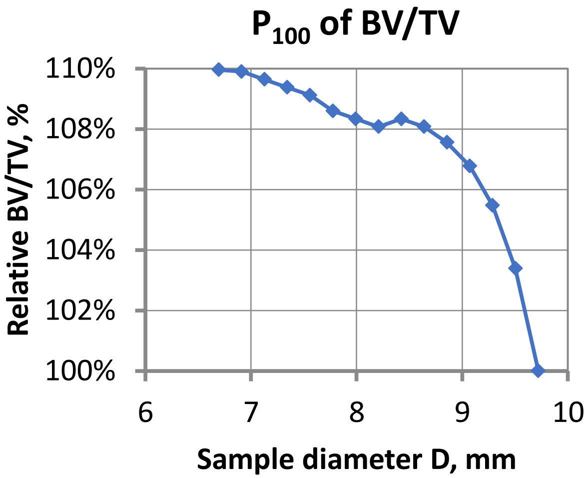
# Results

As a result of processing the binary images, it was determined how the BV/TV values changed with the decrease of the sample diameter for different samples.



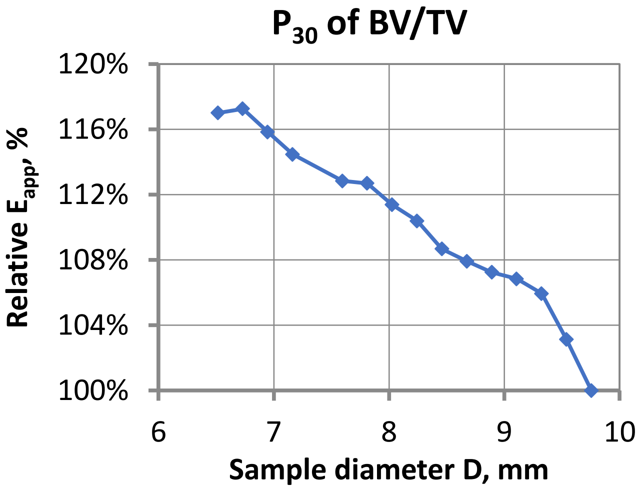



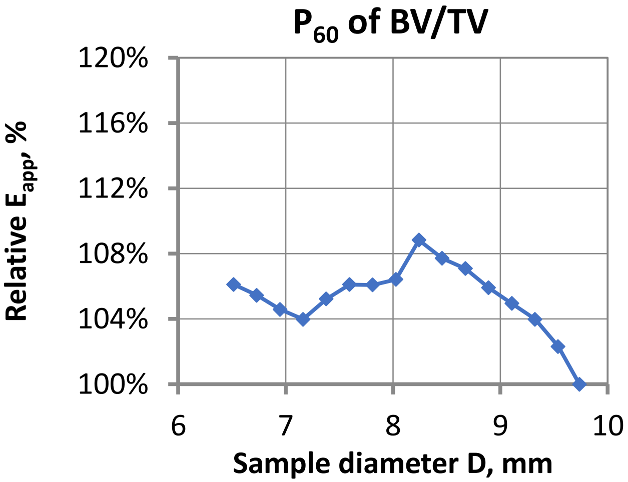



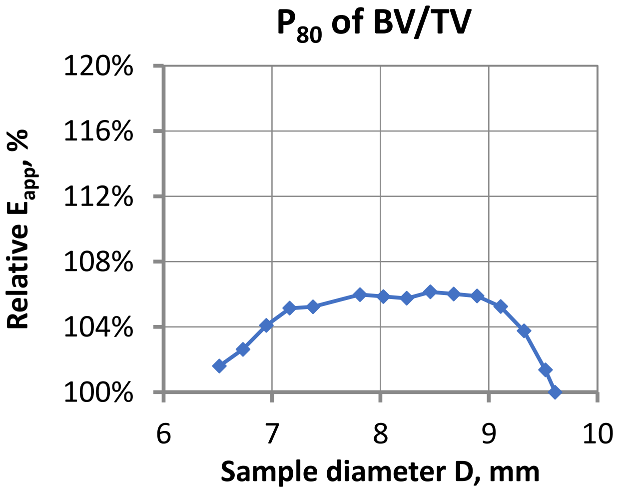



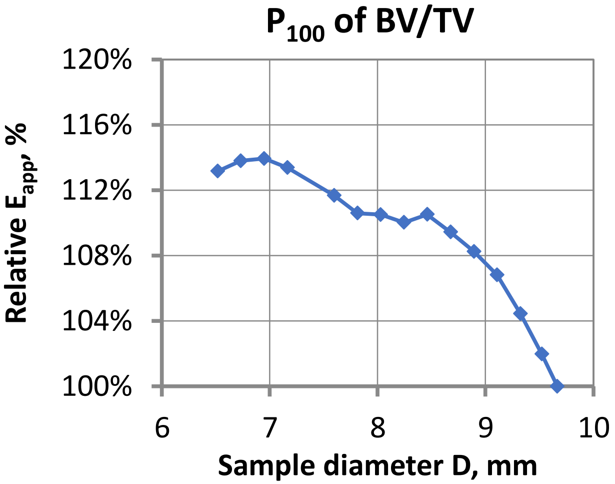
# Results

As a result of numerical analyses, it was determined how apparent Young's modulus changed with the decrease of the sample diameter for different samples.



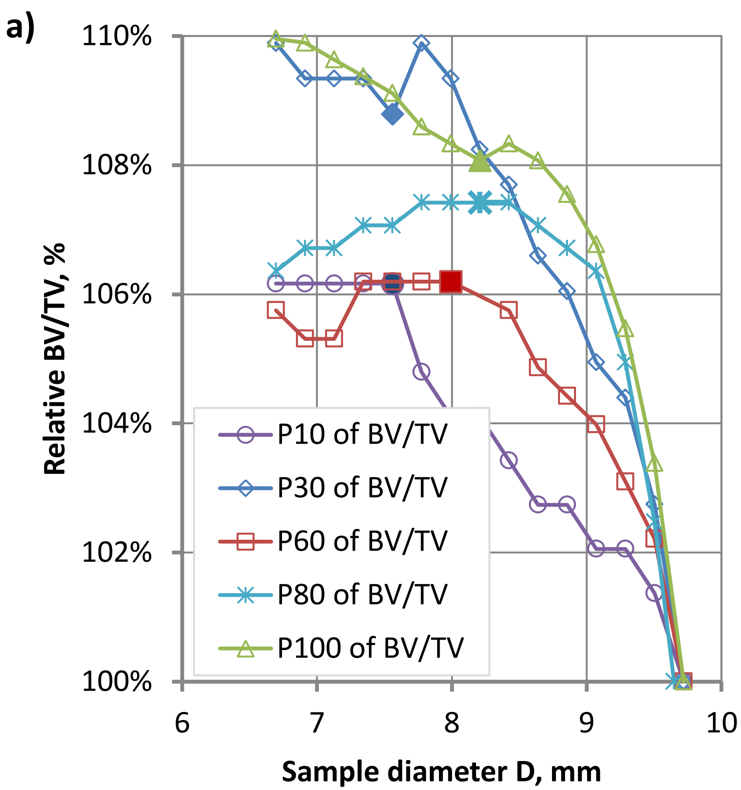



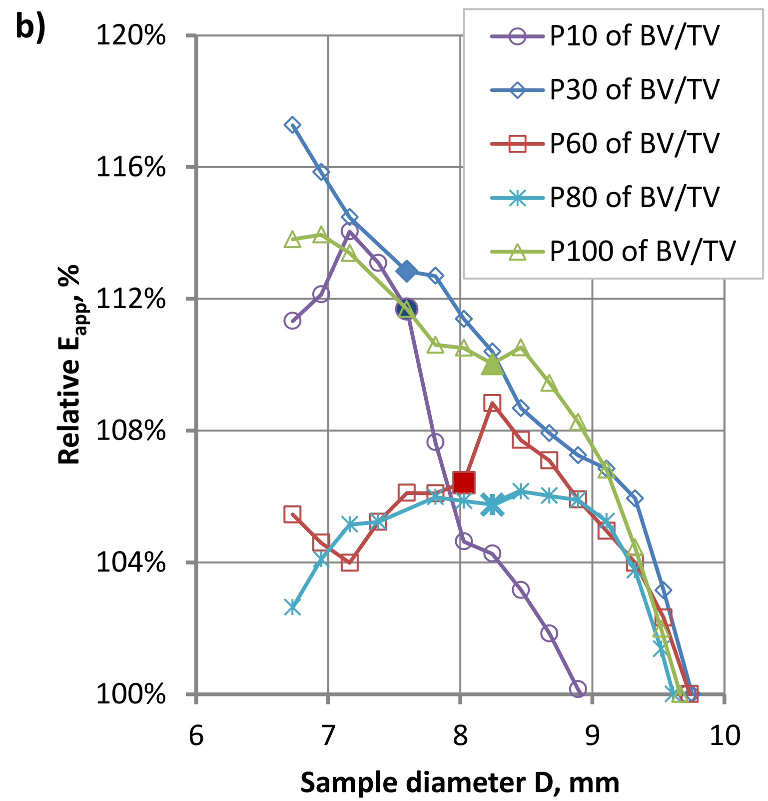



# Results

The results obtained are shown in Fig. a) by the relative values related to BV/TV determined for the largest diameter $\mathbf{D_{max}}$ = 9.72mm. Fig. b) shows in a similar convention the changes in the value of the apparent Young's modulus $E_{app}$ determined during the μFE analyzes.



# Best-fit cylinder. Definition

A three-dimensional matrix is used to determine the cylinder of best fit, which is a digital image of the sample structure. Individual layers of the three-dimensional matrix, selected along the height of the sample, were analyzed. Treating each layer as an image, a Sobel filter was applied to define the edges of the sample edge on that layer. Using the $\mathbf{x_{in}}$ and $\mathbf{y_{in}}$ coordinates of the sample edge points, the mean square error minimization algorithm was used, determining the location of the centre $\mathbf{a_n}$, $\mathbf{b_n}$ and the radius $\mathbf{r_n}$ of the circle of the best fit. The error function defining the sum of radial errors for individual points of the sample edge in the form (1) was minimized:

$$\boldsymbol{\rho_n = \min \sum_i \left( (x_{in} - a_n)^2 + (y_{in} - b_n)^2 \right) - r_n^2} \quad \textbf{(1)}$$

where:

**i** – index of the point forming the edge of the sample,

**n** – index of the analyzed layer.

# Best-fit cylinder. Results

As a result of the calculations, vectors $\mathbf{a_n}$, $\mathbf{b_n}$ and $\mathbf{r_n}$ are created with a length **n** equal to the number of layers, which successively determine the location of the center and the radius of the circle of the best fit on the individual layers of the matrix. It was assumed that the positions of the center of the cylinder of the best fit are determined by the maximum values in the vectors $\mathbf{a_n}$ and $\mathbf{b_n}$, respectively, while the radius of the cylinder of the best fit is determined by the minimum value in the vector $\mathbf{r_n}$.

As a result of applying the best-fit cylinder algorithm, appropriate values of the $\mathbf{D_n}$ diameters were determined. The obtained results are presented for selected samples in Tab. 2. On the courses of relative values shown for individual samples on Fig. a) and Fig. b) in points corresponding to the best-fit cylinder diameters were distinguished by means of filled markers.

*Tab. 2. Best-fit cylinder diameters*

| | **Sample** | | | | |
|---|---|---|---|---|---|
| | **$P_{10}$ of BV/TV** | **$P_{30}$ of BV/TV** | **$P_{60}$ of BV/TV** | **$P_{80}$ of BV/TV** | **$P_{100}$ of BV/TV** |
| **Diameter $D_n$** | 7.56mm | 7.632mm | 7.992mm | 8.28mm | 8.208mm |

# Best-fit cylinder. Analysis

Analysis of the position of the points corresponding to the best-fit cylinder diameters $\mathbf{D_n}$ in the BV/TV relative plots (Fig a) shows that these points divide the corresponding curves into two ranges. In the range from $\mathbf{D_{max}}$ to $\mathbf{D_n}$, the values of BV/TV increases dynamically. In the range of diameters below $\mathbf{D_n}$, the BV/TV values slightly increase for samples $P_{30}$ and $P_{100}$, they stabilize for samples $P_{10}$ and $P_{60}$ and even decrease as it is for samples $P_{80}$. The BV/TV values calculated using the samples with the $\mathbf{D_{max}}$ are on average low by **7%** compared to the BV/TV values calculated using the samples with the $\mathbf{D_n}$.

A similar division into the two ranges of the relative $\mathbf{E_{app}}$ plots due to the distinction of points corresponding to the best-fit cylinder diameters $\mathbf{D_n}$ can be seen in Fig b). The apparent Young's modulus $\mathbf{E_{app}}$ values for samples with $\mathbf{D_{max}}$ diameter are on average **9%** lower than the $\mathbf{E_{app}}$ values for samples with $\mathbf{D_n}$ diameter.

# Conclusions

Due to the use of mechanical treatment of biological material in the process of obtaining a sample to determine indicators of the trabecular structure, damage appears on its surface. This damage leads to shape defects of the sample outline. The method of cutting out samples also does not ensure the parallelism of the bases of the cylinder and the perpendicularity of the bases and the generatrix of the cylinder. Therefore, it is necessary to select the theoretical shape of the cylinder from the scanned images. The work presents a method for determining the parameters of this cylinder based on the best-fit cylinder algorithm.

Determination of the trabecular bone structure indices with the use of samples with a diameter resulting from the cutting process leads to an underestimation of the BV/TV index for the structure under study. On the surfaces of such samples, there are areas in which the mineral fraction BV is missing, which, at a given volume of TV, leads to an underestimation of the BV/TV ratio. Further research should be carried out on how the indicated effect influences the values of other indices of the trabecular structure.

Deficiencies of the mineral fraction in some sections of the sample contribute to the reduction of its stiffness. This leads to the underestimation of the apparent Young's modulus determined in the μFE analysis. The use of the best-fit cylinder algorithm makes it possible to indicate the diameter of the sample so that its entire volume is filled with the mineral fraction in a manner resulting from the bone structure contained in the sample outline.