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Article

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Constructing the dependence between the Young's modulus value and the Hounsfield units of spongy tissue of human femoral heads

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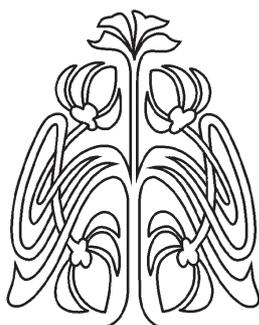
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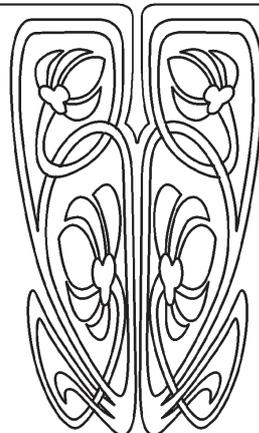
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НАУЧНЫЙ
ОТДЕЛ





Abstract. Patient-specific biomechanical modeling requires not only the geometric model of the studied object of a particular patient, but also the mechanical properties of its tissues. Quantitative computed tomography provides the initial data for geometric modeling, as well as data on X-ray density (Hounsfield units) of the object. It is known that Hounsfield units correlate with mineral density of the scanned objects, as well as with their strength properties. The aim of this study was to determine the relationship between Hounsfield units and Young's modulus values of human femoral heads spongy tissue. This study was conducted on samples of femur bones spongy tissue. The tissue was obtained from patients who underwent total hip replacement for coxarthrosis. Samples were scanned on a Toshiba Aquilion 64 computed tomograph and then subjected to uniaxial compression on an Instron 5944 universal testing machine. As a result of the study, the average Hounsfield units were obtained for each sample, as well as the Young's modulus values. Regression dependencies were calculated linking the Hounsfield units and the Young's modulus values of samples of femoral heads spongy tissue in different types of diseases. The obtained dependences allow one to determine Young's modulus value of femoral heads spongy bone noninvasively for a particular patient, depending on his disease, and using it in the process of preoperative planning. Also, the obtained dependencies can be used in biomechanical modeling of diseases and injuries of vertebral-pelvic complex of a particular patient treatment and can be implemented in medical decision support system in surgery of vertebral-pelvic complex.

Keywords: quantitative computed tomography, bone mineral density, Hounsfield units, Young's modulus

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Научная статья

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Построение зависимости между значением модуля Юнга и числами Хаунсфилда губчатой кости головок бедра

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Аннотация. Пациент-ориентированное биомеханическое моделирование требует знаний не только о геометрической модели исследуемого объекта конкретного пациента, но и о механических свойствах его тканей. Количественная компьютерная томография предоставляет исходные данные для геометрического моделирования, а также данные о рентгеновской плотности (числах Хаунсфилда) исследуемого объекта. Известно, что числа Хаунсфилда коррелируют с минеральной плотностью сканируемых объектов, а также с их прочностными свойствами. Цель исследования состояла в определении зависимости между числами Хаунсфилда и значениями модуля Юнга губчатой ткани головок бедренных костей человека. Данное исследование проведено на образцах губчатой костной ткани бедренных костей пациентов, перенесших тотальное эндопротезирование тазобедренного сустава по поводу коксартроза. Образцы сканировали на компьютерном томографе Toshiba Aquilion 64 и затем подвергали одноосному сжатию на универсальной испытательной машине Instron 5944. В результате исследования для каждого образца были получены средние числа Хаунсфилда, а также значения модулей Юнга. Были рассчитаны регрессионные зависимости, связывающие числа Хаунсфилда и значения модуля Юнга образцов губчатой ткани головок бедренных костей при разных типах заболеваний. Полученные зависимости позволяют неинвазивно определить значение модуля Юнга губчатой кости головок бедренной кости для конкретного пациента в зависимости от его заболевания и использовать его в процессе предоперационного



планирования. Также полученные зависимости могут быть использованы при биомеханическом моделировании вариантов лечения заболеваний и повреждений позвоночно-тазового комплекса конкретного пациента и внедрены в систему поддержки принятия врачебных решений в хирургии позвоночно-тазового комплекса.

Ключевые слова: количественная компьютерная томография, минеральная плотность костной ткани, число Хаунсфилда, модуль Юнга

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Introduction

Biomechanics as a tool for surgical treatment planning and predicting the consequences of treatment is increasingly used in an integrated approach to the preparation for surgery in recent years. At the same time, it is obvious that modeling based on averaged data (whether geometric parameters or materials properties) is unable to provide a sufficient degree of accuracy in predicting the outcome of treatment for a particular patient. In this regard, determination of the mechanical characteristics of patient's tissues is an extremely important and relevant stage of patient-specific biomechanical modeling.

One of the methods for determining in vivo mechanical characteristics of a particular patient's bone tissue is based on the analysis of computed tomography (CT) data. Bone density according to CT data (Hounsfield units or HU) strongly correlates with the volume bone mineral density [1, 2], as well as with mechanical strength of bone tissues [3–5].

When performing the study, CT images are transformed by convolution kernels. The use of convolution kernel can significantly change the Hounsfield numbers of tissues relative to their initial values [6]. It is known that different convolution kernels change Hounsfield numbers in different ways [4, 7, 8]. Therefore, the problem of choosing the convolution kernel when performing quantitative CT is non-trivial, and to obtain the relationship between Young's modulus values and Hounsfield units of bone tissue, it is necessary to first calibrate the tomograph [9, 10].

In many studies, authors attempted to construct dependencies between Hounsfield units and mineral density of tissues [3, 11, 12]. But in most cases the dependency is based on a small data set.

As a rule, authors devote their work to obtaining the relationship between Young's modulus values and bone mineral density estimated by densitometry [13]. This method is not very convenient when it is necessary to numerically solve biomechanics problem based on initial CT data of a particular patient. Therefore, the problem of determining



the relationship between Young's modulus values and initial data of quantitative CT (which are Hounsfield units) arises. For example, in [11], in addition to constructing the relationship between HU and density, the authors obtained a formula for calculating Young's modulus, after which the relationship was verified using mechanical experiments. A significant disadvantage of this work is that all the studies were conducted on rabbits' bones. Thus, the obtained dependences may not be completely accurate in case of human bone tissue studies [10].

Authors in [14] showed that the best correlation between mechanical properties and density is observed for spongy bone tissue. They also found that the power function, compared to the linear function, gives better correspondence between density and Young's modulus values.

In [15], a correlation was established between X-ray density of spongy bone tissue of the ankle joint and its elasticity modulus. At the same time, the authors did not specify CT settings, and the number of samples was only 42 pieces. Moreover, bone tissue material was collected from human cadavers.

The purpose of this study was to determine the relationship between Hounsfield units and Young's modulus values of human femoral heads spongy tissue. Within the framework of this study, dependencies were also obtained for various diseases of hip joint. The obtained dependences allow to noninvasively determine the Young's modulus value of the femoral heads spongy bone for a particular patient, depending on his disease, and using it in preoperative planning process.

1. Materials and methods

To identify the relationship between Hounsfield units and Young's modulus of the femoral heads spongy bone, a full-scale experiment was conducted.

Transfer of bone tissue of patients from Research Institute of Traumatology, Orthopedics and Neurosurgery of Razumovsky Saratov State Medical University was approved by the Ethics Committee. The transfer was performed in the framework of the implementation agreement of the Russian Foundation for Advanced Research project. The aim of the project is to develop a prototype of a decision-making medical supporting system to improve effectiveness of treatment of patients with vertebral-pelvic complex injuries and diseases. One of the project objectives is to create and to fill in the "Mechanical" database which will contain mechanical characteristics of bone tissues [16]. Bone tissue research was carried out within the framework of this project objective.

The femoral heads removed no later than a day after the hip replacement surgery were taken from the hospital for further examination. The samples were prepared using a hand-held metal hacksaw with the initial fragments fixed in a vise. Samples from 1 to 4 were prepared from one fragment of the femoral head. An average prepared sample was a rectangular parallelepiped with an edge size of at least 5 and not more than 10 mm [13].

In order to avoid drying out and loss of properties, the prepared fragments were packed in a plastic film, after which their CT scan was performed on a Toshiba Aquilion 64 computed tomograph. During the study, the convolution kernel FC17 was selected as the tomograph settings [9, 17].

Samples of the femoral heads of 150 patients were scanned on CT. For each head the first letter of the last name, age (year of birth), gender, volume of the experimental sample, and the average value of Hounsfield units were recorded.

Next, the femoral head fragments were subjected to uniaxial compression experi-



ments to determine their Young's modulus on Instron 5944 universal testing machine. The preload value was 10 N, the loading speed was 30 mm/min. Shape of the samples made it possible to measure their cross-sectional area by simple measurements of length and width using an electronic vernier caliper.

As a result of the experiments maximum values of stress and displacement were determined, "stress-strain" graphs were plotted (Fig. 1) and Young's modulus values were calculated. Next, the average values of Young's modulus were determined as the arithmetic mean for bone samples within a single fragment of the femoral head. But since the prepared samples had different volumes, the average values of Young's modulus were determined as the weighted average harmonic for bone samples within a single fragment of the femoral head. Further, the study used Young's modulus values as a weighted average harmonic. Table 1 shows examples of the results of the study for three randomly selected patients. In total, data for 150 patients was obtained.

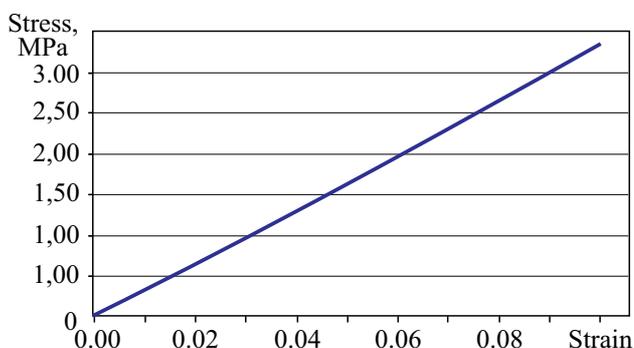


Fig. 1. "Stress-strain" graph for spongy bone of the patient's femoral head fragment (S., 1962, female)

Table 1

Young's modulus of femoral head fragments determined from full-scale experiments

Identifier	ICD-10 code	Young's module, MPa	
		Experimental value a	Weighted average harmonic value
B., 1951, male	M 16.0	48.2	42.6
		37.7	
		40.2	
		45.7	
B., 1954, female	M 16.0	116.7	133.5
		150.3	
T., 1953, female	M 16.1	74.6	73.1
		71.4	

Next, a statistical analysis of the accumulated data was carried out in order to identify the regression relationship between Young's modulus and Hounsfield units. Statistical analysis was performed in the Microsoft Office 2019.

Regression analysis was used to identify factors, degree, and form of influence of the results of field and numerical experiments on the value of the Young's modulus [18, 19].

The following information was analyzed: age and gender of the patient; nosology (disease code according to ICD 10); Hounsfield units (HU); Young's modulus determined from the data of full-scale experiment. The last indicator was considered as a dependent variable (the resulting attribute).

At the first step, statistical analysis of the experimental data and the results of CT studies was carried out without taking into account specific features (age, gender, ICD-10 code), at the second – taking into account patient's gender, at the third – taking into



account ICD-10 code. Hounsfield units and Young’s modulus had a normal distribution (Kolmogorov – Smirnov test, the significance level was 5%).

In the statistical analysis of experimental data and the results of CT studies, models of linear multiple regression (additive model) and linear regression in logarithms (multiplicative model) were constructed and analyzed. The level of statistical significance of the coefficients was less than 5%.

2. Results and discussion

At the first step, the dependences between Young’s modulus and Hounsfield units were studied without taking into account specific features (age, gender, ICD-10 code). A specified linear multiple regression model was constructed:

$$E = 0.20 * HU + 5.98, \quad R^2 = 0.67, \quad (1)$$

where E is Young’s modulus, HU is Hounsfield unit. R^2 is the coefficient of determination.

The level of statistical significance of the coefficient for HU variable was less than 0.1%, but the free term is statistically insignificant at 5% level, so the model (1) can be implemented as:

$$E = 0.22 * HU, \quad R^2 = 0.67. \quad (2)$$

The constructed model (2) satisfies the standard assumptions of linear regression (normality of the initial data distribution and model residuals, homoscedasticity) and explains 67% of the variation in the Young’s modulus values (Figure 2).

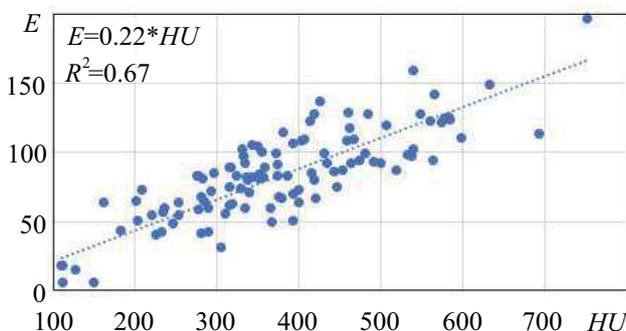


Fig. 2. Dot diagram: Hounsfield units values (CT data) are plotted along abscissa axis, and Young’s modulus values (data from full-scale experiments) are plotted along ordinate axis

A slightly higher value of the determination coefficient can be obtained by specifying the multiplicative model:

$$E = e^{1.17 * Ln(HU) - 2.55}, \quad R^2 = 0.68. \quad (3)$$

Model (3) explains more than 68% of the dependent variable variation. The advantage of this model is high (at the level of less than 0.001%) significance of the coefficients.

The conducted studies allowed us to calculate the predicted values of the Young’s modulus for the considered tissues and errors in them. The difference in values between the Young’s modulus determined from the full-scale experiment data and predicted using model (2) was on average 19%, and when using model (3) — 20%.

The conducted studies allowed us to calculate the predicted values of the Young’s modulus for the considered

Next, step 2 of the study was carried out — identifying the dependence of the Young’s modulus on the Hounsfield units analysis, taking into account patient’s gender.

The linear regression of Young’s modulus versus Hounsfield units for the female patients’ femoral heads was more adequate than for male patients (the values of the determination coefficients were 0.72 and 0.62, respectively), but the Chow test showed no structural differences. The constructed models are presented in Table 2.



Based on the constructed models (4)–(7), predicted values of the Young's modulus and errors in them for the studied tissues were determined. The difference between the Young's modules determined from the full-scale experiment data and predicted by formulas (4)–(7) are presented in Table 3.

From previously obtained results and data in Table 3, it can be seen that the introduction of a gender attribute in the analysis did not significantly affect the improvement of the predicting result. In linear regression models, there is an improvement of 1 unit, and in the analysis of the results of the multiplicative model (for females), there is a deterioration of 1 unit.

To improve the results of the Young's modulus values prediction, the 3rd stage of the study was carried out — an analysis of its dependence on Hounsfield units, taking into account the code of international classification of diseases (ICD-10). In the experiment, bone fragments of patients with ICD-10 codes were studied: M16.0, M16.1, M16.2, M16.3, M16.5, M16.6, M16.7, M17.0, M21.9, M84.1, M87.0, M87.2, M95.8, M95.9 (Table 4).

Table 2

Linear multiple regression models and multiplicative models based on gender

Gender	Models
Male	$E=0.20*HU+8.01, R^2 = 0.62$ (4)
	$E=e^{1.02*ln(HU)^{1.68}}, R^2 = 0.69$ (5)
Female	$E=0.22*HU+3.74, R^2 = 0.72$ (6)
	$E=e^{1.26*ln(HU)^{3.04}}, R^2 = 0.68$ (7)

Table 3

The difference between the Young's modules determined by the full-scale experiment data and predicted by the formulas (4)–(7)

Gender	Models	Average difference, %
Male	(4)	18
	(5)	18
Female	(6)	18
	(7)	21

Table 4

Number of studies for each ICD-10 code

ICD-10 code	Number of studies	ICD-10 code	Number of studies
M16.0	85	M17.0	2
M16.1	23	M21.9	2
M16.2	6	M84.1	6
M16.3	3	M87.0	12
M16.5	1	M87.2	1
M16.6	3	M95.8	1
M16.7	3	M95.9	2

The dependence of Young's modulus on Hounsfield units for each ICD-10 code was studied, the volume of full-scale experiments carried out for each of them amounted to at least 5 measurements.

Data on ICD-10 codes (M16.3, M16.5, M16.6, M16.7, M17.0, M21.9, M87.2, M95.8, M95.9), for each of which less than five full-scale experiments were conducted, were collected together. Generalized models were obtained for these data. The constructed models are shown in Table 5.



Table 5

Linear multiple regression models and multiplicative models taking into account the ICD-10 code

ICD-10 code	Models
M16.0	$E = 0.19*HU + 14.46, R^2 = 0.64$ (8)
	$E = e^{1.05*\ln(HU)-1.77}, R^2 = 0.74$ (9)
M16.1	$E = 0.24*HU - 5.79, R^2 = 0.71$ (10)
	$E = e^{1.08*\ln(HU)-2.02}, R^2 = 0.75$ (11)
M16.2	$E = 0.18*HU - 50.10, R^2 = 0.67$ (12)
	$E = e^{0.64*\ln(HU)+0.95}, R^2 = 0.61$ (13)
M84.1	$E = 0.18*HU + 13.67, R^2 = 0.75$ (14)
	$E = e^{0.79*\ln(HU)-0.28}, R^2 = 0.78$ (15)
M87.0	$E = 0.17*HU + 12.20, R^2 = 0.80$ (16)
	$E = e^{0.82*\ln(HU)-0.49}, R^2 = 0.78$ (17)
M16.3, M16.5, M16.6, M16.7, M17.0, M21.9, M87.2, M95.8, M95.9	$E = 0.20*HU + 4.55, R^2 = 0.60$ (18)
	$E = e^{1.56*\ln(HU)-4.96}, R^2 = 0.66$ (19)

Based on the constructed models (8)–(19), the predicted values of the Young’s modulus and errors in them for the studied tissues were determined. The differences between Young’s modulus determined from the full-scale experiment data and predicted by formulas (8)–(19) are presented in Table 6.

Table 6

The difference between Young’s modulus determined by the full-scale experiment data and predicted by the formulas (8)–(19)

ICD-10 code	Model	Average difference, %
M16.0	(8)	27
	(9)	16
M16.1	(10)	14
	(11)	16
M16.2	(12)	16
	(13)	14
M84.1	(14)	11
	(15)	12
M87.0	(16)	16
	(17)	16
M16.3, M16.5, M16.6, M16.7, M17.0, M21.9, M87.2, M95.8, M95.9	(18)	20
	(19)	27

Table 6 shows that when considering the data separately for each ICD-10 code, the difference in values between the Young’s modulus determined from the full-scale



experiment data and predicted by formulas (8)–(18) does not exceed 16% on average. The exception is the linear regression models for the M16.0 code and the last line in Table 6, which contains codes with studies of less than 5 dimensions. At the same time, it is worth noting that the multiplicative model for the M16.0 code gives results with an average error of not more than 16%.

It was found that the Young's modulus values obtained during the full-scale experiment almost do not differ from the predicted values obtained from the results of the numerical experiment for the femoral heads tissues. The presence of an error in the predicted Young's modulus value is due to the significant heterogeneity of bone tissue due to the presence of pathological processes (osteonecrosis, osteosclerosis, osteoporosis). It is worth noting that the error for the predicted Young's modulus values, determined by formulas taking into account the ICD-10 code, is much lower. On this basis, it is advisable to use them in future.

Chow tests at a significance level of 5% showed no structural differences in the models constructed for different ICD-10 codes. The case for M16.1 stands out slightly, but there were no statistically confirmed deviations from the general trend. This makes it possible to use a single pair regression model (2) or (3) for predicting purposes.

It should be emphasized that the revealed dependencies between Young's modulus values and Hounsfield units can only be used for processing CT studies performed on Toshiba Aquilion 64 tomograph, since different models of scanning devices can give different values of HU [20]. Moreover, it was found that the CT study protocols also have a significant effect on Hounsfield units [9]. Thus, as a continuation of this work, we see the study of the influence of manufacturer, the model of tomograph, as well as its settings on the reliability of the results obtained using the proposed formula. In the event that the predicting is not accurate enough, it is necessary to calculate correction factors or re-specify the model taking into account new data.

To determine the correction coefficients for each tomograph, calibrated samples of an aqueous solution of potassium hydroorthophosphate [9, 14, 17] with a known mineral density could be scanned, after which it will be possible to obtain similar regression dependencies and final models. By comparing the existing and newly obtained models, it will be possible to determine correction factors for each specific tomograph.

Conclusion

In the study, the relationships between Hounsfield units and Young's modulus of bone tissue were obtained without taking into account specific features (age, gender, ICD-10 code) and also taking into account patient's gender and ICD-10 code. It was revealed that the error for the predicted Young's modulus values, determined by formulas taking into account ICD-10 code, does not exceed 16%. Based on this, it is advisable to use them in future.

These formulas can be used to determine the mechanical characteristics of bones in biomechanical modeling of surgical treatment. This approach will allow one to obtain the properties of the particular patient's tissues, which is extremely important for a personalized approach to treatment planning. At the same time, to generalize the obtained formulas, it is necessary to conduct a series of experiments to test them on tomographic studies using tomographs of various manufacturers and modifications.

References

1. Patel S. P., Lee J. J., Hecht G. G., Holcombe S. A., Wang S. C., Goulet J. A. Normative vertebral Hounsfield unit values and correlation with bone mineral density. *Journal of Clinical*



- & *Experimental Orthopaedics*, 2016, vol. 2, no. 14, pp. 1–7. <https://doi.org/10.4172/2471-8416.100014>
2. Kim K. J., Kim D. H., Lee J. I., Choi B. K., Han I. H., Nam K. H. Hounsfield units on lumbar computed tomography for predicting regional bone mineral density. *Open Medicine*, 2019, vol. 14, pp. 545–551. <https://doi.org/10.1515/med-2019-0061>
 3. Khan S. N., Warkhedkar R. M., Shyam A. K. Analysis of Hounsfield unit of human bones for strength evaluation. *Procedia Materials Science*, 2014. vol. 6, pp. 512–519. <https://doi.org/10.1016/j.mspro.2014.07.065>
 4. Giambini H., Dragomir-Daescu D., Huddleston P. M., Camp J. J., An K. N., Nassr A. The effect of quantitative computed tomography acquisition protocols on bone mineral density estimation. *Journal of Biomechanical Engineering*, 2015, vol. 137, no. 11, pp. 114502. <https://doi.org/10.1115/1.4031572>
 5. Cyganik L., Binkowski M., Kokot G., Rusin T., Popik P., Bolechala F., Nowak R. Wrobel Z., John A. Prediction of Young's modulus of trabeculae in microscale using macro-scale's relationships between bone density and mechanical properties. *Journal of the Mechanical Behavior of Biomedical Materials*, 2014, vol. 36, pp. 120–134. <https://doi.org/10.1016/j.jmbbm.2014.04.011>
 6. Michalski A. S., Edwards W. B., Boyd S. K. The influence of reconstruction kernel on bone mineral and strength estimates using quantitative computed tomography and finite element analysis. *Journal of Clinical Densitometry*, 2019, vol. 22, iss. 2, pp. 219–228. <https://doi.org/10.1016/j.jocd.2017.09.001>
 7. Andersen H. K., Jensen K., Berstad A. E., Aalokken T. M., Kristiansen J., von Gohren Edwin B., Hagen G., Martinsen A. C. Choosing the best reconstruction technique in abdominal computed tomography: A systematic approach. *Journal of Computer Assisted Tomography*, 2014, vol. 38, iss. 6, pp. 853–858. <https://doi.org/10.1097/RCT.0000000000000139>
 8. Birnbaum B. A., Hindman N., Lee J., Babb J. S. Multi-detector row CT attenuation measurements: Assessment of intra- and interscanner variability with an anthropomorphic body CT phantom. *Radiology*, 2007, vol. 242, no. 1, pp. 109–119.
 9. Ivanov D. V., Kirillova I. V., Kossovich L. Yu., Bessonov L. V., Petraikin A. V., Dol A. V., Ahmad E. S., Morozov S. P., Vladzimirskyy A. V., Sergunova K. A., Kharlamov A. V. Influence of convolution kernel and beam-hardening effect on the assessment of trabecular bone mineral density using quantitative computed tomography. *Izvestiya of Saratov University. New Series. Series: Mathematics. Mechanics. Informatics*, 2020, vol. 20, iss. 2, pp. 205–219. <https://doi.org/10.18500/1816-9791-2020-20-2-205-219>
 10. Currey J. D. Tensile yield in compact bone is determined by strain, post-yield behaviour by mineral content. *Journal of Biomechanics*, 2004, vol. 37, iss. 4, pp. 549–556. <https://doi.org/10.1016/j.jbiomech.2003.08.008>
 11. Chen W.-P., Hsu J.-T., Chang C.-H. Determination of young's modulus of cortical bone directly from computed tomography: A rabbit model. *Journal of the Chinese Institute of Engineers*, 2003, vol. 26, no. 6, pp. 737–745. <https://doi.org/10.1080/02533839.2003.9670828>
 12. Giambini H., Dragomir-Daescu D., Nassr A., Yaszemski M. J., Zhao C. Quantitative computed tomography protocols affect material mapping and quantitative computed tomography-based finite-element analysis predicted stiffness. *Journal of Biomechanical Engineering*, 2016, vol. 138, iss. 9, pp. 091003-1–091003-7. <https://doi.org/10.1115/1.4034172>
 13. Helgason B., Perilli E., Schileo E., Taddei F., Brynjolfsson S., Viceconti M. Mathematical relationships between bone density and mechanical properties: A literature review. *Clinical Biomechanics*, 2008, vol. 23, no. 2, pp. 135–146. <https://doi.org/10.1016/j.clinbiomech.2007.08.024>
 14. Witt R. M., Cameron J. R. *Improved Bone Standard Containing Dipotassium Hydrogen Phosphate Solution for The Intercomparison of Different Transmission Bone Scanning Systems*. United States: N. p., 1971. 6 p. <https://doi.org/10.2172/4054820>



15. Omelchenko T. M., Buryanov O. A., Lyabakh A. P., Mazevich V. B., Shidlovsky M. S., Musienko O. S. Correlation of elastic modulus and x-ray bone density in the area of the ankle joint. *Orthopedics, Traumatology and Prosthetics*, 2018, no. 3, pp. 80–84 (in Ukraine). <http://dx.doi.org/10.15674/0030-59872018380-84>
16. Dmitriev P. O., Golyadkina A. A., Bessonov L. V., Kirillova I. V., Kossovich L. Yu., Falkovich A. S. The dependence of Young's modulus of trabecular bony tissue on its density according to computed tomography. *Progress in Biomedical Optics and Imaging – Proceedings of SPIE*, 2019, vol. 11229, article no. 112291L. <https://doi.org/10.1117/12.2545077>
17. Petraikin A. V., Ivanov D. V., Akhmad E. S., Sergunova K. A., Nizovtsova L. A., Petryaykin F. A., Ruzov S. A., Kirilova I. V., Kossovich L. Yu., Bessonov L. V., Dol A. V., Vladzimirskyy A. V., Harlamov A. V. Phantom modeling for selection of optimum reconstruction filters in the quantitative computer tomography. *Meditinskaya Fizika* [Medical Physics], 2020, vol. 86, no. 2, pp. 34–44 (in Russian).
18. Glanc S. *Mediko-biologicheskaya statistika* [Medical and Biological Statistics]. Moscow, Praktika, 1998. 459 p. (in Russian).
19. Kobzar' A. I. *Prikladnaya matematicheskaya statistika: Dlya inzhenerov i nauchnyh rabotnikov* [Applied Mathematical Statistics: For Engineers and Scientists]. Moscow, Fizmatlit, 2006. 816 p. (in Russian).
20. Free J., Eggermont F., Derikx L., van Leeuwen R., van der Linden Y., Jansen W., Raaijmakers E., Tanck E., Kaatee R. The effect of different CT scanners, scan parameters and scanning setup on Hounsfield units and calibrated bone density: A phantom study. *Biomedical Physics & Engineering Express*, 2018, vol. 4, no. 5, pp. 12. <https://doi.org/10.1088/2057-1976/aad66a>

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