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Construction of a representative model based on computed tomography

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Abstract

© PNRPU. The simulation of the stress-strain state of porous or multiphase media is an important task nowadays. The application of the mathematical model of continuum mechanics to such media will make it possible to extend the scope of the problems to be solved. The development of nondestructive methods of control, such as computed tomography, allows obtaining data on the structure of various heterogeneous materials. This task is especially important in the areas of clinical medicine and biology. The paper presents the method aimed at determining mechanical properties of a representative element using computed tomography. Based on the finite element method for a given region, a finite-element ensemble is constructed using the scanning data on a computer tomograph of a real sample. For the obtained sample, numerical experiments are performed in the kinematic formulation, after which the problem of the stress-strain state is solved. The stresses obtained as a result of the calculations are averaged and used to determine the components of the elastic constant tensor. Thus, the anisotropic properties of the representative element are determined. To determine the orthotropic properties of the representative element, a target function is introduced, the arguments of which are unknown directions of orthotropy. These unknown directions are determined from the condition of minimizing the objective function. The transformation of the rotation to an anisotropic matrix of elastic constants makes it possible to determine the components of the elastic constant tensor in the orthotropic axes. As an illustration of the technique, calculations of a porous sample are given in the paper, and the obtained results are evaluated. For the quantitative comparison, the invariant of the stress tensor is used. The obtained results illustrate not only a sufficient accuracy of describing the medium in terms of continuity, but also a discrepancy in the results in the case of large porosity.

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Keywords

Anisotropy, Computed tomography, Finite element method, Orthotropic axes, Orthotropy, Representative element

References

[1] Gross T., Pahr D.H., Zysset P.K. Morphology–elasticity relationships using decreasing fabric information of human trabecular bone from three major anatomical locations. Biomech. Model Mechanobiol, 2013, vol. 12, pp. 793-800.

[2] Schwen L.O., Wolfram U., Rumpf M. Determining effective elasticity parameters of microstructure materials. 15th Workshop on the Finite Element Method in Biomedical Engineering, Biomechanics and Related Fields., July 2008, pp. 26-41.

[3] Cowin S.C. Continuum Mechanics of Anisotropic Materials. Springer-Verlag, New York, 2013, 425 pp.

[4] Dempster DW, Compston JE, Drezner MK, et al. Standardized nomenclature, symbols, and units for bone histomorphometry: a 2012 update of the report of the ASBMR Histomorphometry Nomenclature Committee. J. Bone Miner Res., 2013, vol. 28, pp. 1-16.

[5] Bousson V, Bergot C, Sutter B, Levitz P, Cortet B. Trabecular bone score (TBS): available knowledge, clinical relevance, and future prospects. Osteoporos Int, 2012, vol. 23, no. 5, pp. 1489-501.

[6] Roux J.P., Wegrzyn J., Boutroy S., Bouxsein M.L., Hans D., Chapurlat R. The predictive value of trabecular bone score (TBS) on whole lumbar vertebrae mechanics: an ex vivo study. Osteoporos Int., 2013, vol. 24, no. 9, pp. 2455-60.

[7] Nassar K., Paternotte S., Kolta S., Fechtenbaum J., Roux C., Briot K. Added value of trabecular bone score over bone mineral density for identification of vertebral fractures in patients with areal bone mineral density in the non-osteoporotic range. Osteoporos Int., 2014, vol. 25, no. 1, pp. 243-9.

[8] Leslie WD, Aubry-Rozier B, Lix LM, et al. Spine bone texture assessed by trabecular bone score (TBS) predicts osteoporotic fractures in men: The Manitoba Bone Density Program. Bone, 2014, vol. 67, pp. 10-4.

[9] Konoplev Yu.G., Mitryaykin V.I., Sachenkov O.A. Primeneniye matematicheskogo modelirovaniya pri planirovanii operatsii po endoprotezirovaniyu tazobedrennogo sustava [Application of mathematical modeling in the planning of surgery for hip arthroplasty]. Uchenyye zapiski Kazanskogo universiteta. Seriya: Fiziko-matematicheskiye nauki, 2011, vol. 153, no. 4, pp. 76-83.

[10] Konoplev Yu.G., Mazurenko A.V., Sachenkov O.A., Tikhilov R.M. Numerical study of the influence of the degree of undercoverage of the acetabular component on the load-bearing capacity of hip joint endoprosthesis. Russian Journal of Biomechanics, 2015, vol. 19, no. 4, pp. 283-295.

[11] Sachenkov O.A., Hasanov R.F., Andreev P.S., Konoplev Yu.G. Numerical study of stress-strain state of pelvis at the proximal femur rotation osteotomy. Russian Journal of Biomechanics, 2016, vol. 20, no. 3, pp. 220-232.

[12] Kichenko A.A., Tverier V.M., Nyashin Y.I., Zaborskikh A.A. Experimental determination of the fabric tensor for cancellous bone tissue. Russian Journal of Biomechanics, 2011, vol. 15, no. 4, pp. 66-81.

[13] Kichenko A.A., Tver'ye V.M., Nyashin Yu.I. Matematicheskoye opisaniye povedeniya gubchatoy kostnoy tkani pod nagruzkoy [Mathematical description of the behavior of spongy bone under load]. Matematicheskoye modelirovaniye v yestestvennykh naukakh, 2013, no. 1, pp. 84-85.

[14] Dyadyukina A.D., Kichenko A.A. Matematicheskoye modelirovaniye trabekulyarnoy kostnoy tkani [Mathematical modeling of trabecular bone tissue]. Matematicheskoye modelirovaniye v yestestvennykh naukakh, 2016, vol. 1, pp. 627-630.

[15] Huiskes R., Van Rietbergen B., Odgaard A., Kabel J. Direct Mechanics assessment of elastic symmetries and properties of trabecular bone architecture. J. Biomech., 1996, vol. 29(12), pp. 1653-1657.

[16] Maquer G., Musy S.N., Wandel J., Gross T., Zysset P.K. Bone Volume Fraction and Fabric Anisotropy Are Better Determinants of Trabecular Bone Stiffness Than Other Morphological Variables. Journal of Bone and Mineral Research., 2015, vol. 30, no. 6, pp. 1000–1008. DOI: 10.1002/jbmr.2437.

[17] Bouxsein ML, Boyd SK, Christiansen BA, Guldberg RE, Jepsen KJ, Müller R. Guidelines for assessment of bone microstructure in rodents using micro–computed tomography. J. Bone Miner Res, 2010, vol. 25, pp. 1468–86.

[18] Zysset P.K., Curnier A. An alternative model for anisotropic elasticity based on fabric tensors. Mechanics of Materials, 1995, vol. 21, iss. 4, pp. 243-250.

[19] Zysset P.K. A review of morphology–elasticity relationships in human trabecular bone: theories and experiments. J. of Biomechanics, 2003, vol. 36, pp. 1469-1485.

[20] Gross T., Pahr D.H., Peyrin F. and Zysset P.K. Mineral heterogeneity has a minor influence on the apparent elastic properties of human cancellous bone: a SRmCT-based finite element study. Computer Methods in Biomechanics and Biomedical Engineering, 2012, vol. 15, no. 11, pp. 1137-1144.

[21] Fosbinder R., Orth D. Essentials of Radiologic Science. Lippincott Williams & Wilkins, 2011, 392 p.

[22] Otsu N. A threshold selection method from gray-level histograms. IEEE Transactions on Systems, Man, and Cybernetics, 1979, vol. 9, iss. 1, pp. 62-66.

[23] Kazembakhshi S, Luo Y. Constructing anisotropic finite element model of bone from computed tomography (CT). Biomed Mater Eng., 2014, vol. 24, no. 6, pp. 2619-26.

[24] Panyasantisuk J, Pahr DH, Gross T, Zysset PK. Comparison of mixed and kinematic uniform boundary conditions in homogenized elasticity of femoral trabecular bone using micro finite element analyses. J. Biomech Eng., 2015, vol. 137, no. 1, 011002. DOI: 10.1115/1.4028968.

[25] Pahr D.H., Zysset P.K. A comparison of enhanced continuum FE with micro FE models of human vertebral bodies. Journal of Biomechanics, 2009, vol. 42, pp. 455-462.

[26] Zhou B, Liu XS, Wang J, Lu XL, Fields AJ, Guo XE. Dependence of mechanical properties of trabecular bone on platerod microstructure determined by individual trabecula segmentation (ITS). J. Biomech., 2014, vol. 47, no. 3, pp. 702-8.

[27] Pahr DH, Dall'Ara E, Varga P, Zysset PK. HR-pQCTbased homogenised finite element models provide quantitative predictions of experimental vertebral body stiffness and strength with the same accuracy as mFE models. Comput Methods Biomech Biomed Engin., 2012, vol. 15, no. 7, pp. 711-20.

[28] Larsson D, Luisier B, Kersh ME, et al. Assessment of transverse isotropy in clinical-level CT images of trabecular bone using the gradient structure tensor. Ann Biomed Eng., 2014, vol. 42, no. 5, pp. 950-9.

[29] Hazrati Marangalou J, Ito J, van Rietbergen K. A novel approach to estimate trabecular bone anisotropy from stress tensors. Biomech. Model Mechanobiol, 2015, vol. 14, no. 1, pp. 39–48. DOI: 10.1007/s10237–014-0584–6.

[30] Mirkhalaf S.M., Andrade Pires F.M., Simoes Ricardo Determination of the size of the Representative Volume Element (RVE) for the simulation of heterogeneous polymers at finite strains. Finite Elements in Analysis and Design, 2016. vol. 119, no. 15, pp. 30-44. DOI: 10.1016/j.finel.2016.05.004.

[31] Lekhnitskiy S.G. Teoriya uprugosti anizotropnogo tela [Theory of elasticity of an anisotropic body]. Moscow, Nauka, 1977, 416 p.

[32] Gerasimov O., Koroleva E., Sachenkov O. Experimental study of evaluation of mechanical parameters of heterogeneous porous structure. IOP Conference Series: Materials Science and Engineering, 2017, vol. 208, 012013. DOI: 10.1088/1757-899X/208/1/012013.