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# Effect of surgical defect localization on ultimate load-bearing capacity of human femur: finite-element energy-based assessment

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**Abstract**

Elastic properties and toughness of cortical bone tissue are non-uniformly distributed over its anatomical quadrants. This can have an effect on the bone's load-bearing capacity after a surgical resection associated with a removal of tumor-like lesions followed by formation of a sectorial bone defect. The purpose of this work is to evaluate the ultimate load-bearing capacity of the femur with the post-resection defect, taking into account various types of distributions of elastic properties and toughness in different quadrants of a cross section of the bone. The elasticity modulus of the bone tissue in the longitudinal direction of the femur is determined based on a nanoindentation test of a human femoral bone specimen. Based on numerical simulations, it is established that the most dangerous – with regard to the occurrence of a pathological fracture – is the localization of the post-resection defect, when a remaining fragment of the bone tissue is located in the anterior quadrant. In this case, the value of the ultimate load is significantly lower compared to that for other variants of localization of the post-resection defect. A non-uniform distribution of fracture toughness in the cross-section of the femur has a greater effect on the magnitude of the ultimate load than non-uniformity of elastic properties. This should be taken into account when evaluating the ultimate load, since averaging the toughness over the bone's cross-section can result in overestimations. Neglecting non-uniformity of toughness can lead to an incorrect assessment of the ultimate load and to wrong recommendations for postoperative rehabilitation of a patient.



*Keywords:* human femur; nanoindentation; modulus of elasticity; surgical resection; post-resection defect; *J*-integral; toughness; ultimate load

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## 1. Introduction

Bones are the main structural components of a skeleton, providing a continuous shape for a human body; they protect internal organs and transfer muscle forces. Hence, structural integrity of a bone tissue is important, since a bone can withstand loads up to a certain limit before losing its load-bearing capacity. An understanding of mechanisms of bone fracture is required for prophylaxis and prevention of injuries. The most suitable way to underpin quantitative analysis of bone's mechanical behavior is to develop adequate numerical models of a bone, as a whole, and a bone tissue, allowing studies of the causes of bone fractures, to propose ways for their prevention or healing.

Volume fractions and properties of components such as minerals, organic matrix and osteons of the bone tissue in combination with their orientation and distribution significantly influence its mechanical behavior. Differences in the orientation of the constituent components of the bone lead to its anisotropy (transverse isotropy or orthotropy) of properties, and anisotropic properties can manifest both along the length of the bone and the anatomical quadrants (or sides of the cross section of the bone) (Orías, 2005; Rho, 1996). In particular, elastic properties (Rho, 1996) and toughness (Li et al., 2013) of the cortical bone tissue are non-uniform along the bone's circumference (in different anatomical quadrants).

Different properties of bone tissue for different quadrants of the bone cross-section can influence the bone's load-carrying capacity after surgical resection (removal of a tumor-like lesion with formation of a sectorial bone defect). This is due to the fact that a part of the bone remaining after the operation is loaded partially or fully, corresponding its position in the cross section of the bone. Figure 1 shows the scheme of surgical resection.

As a result of surgical resection, the strength of the segment decrease and there is a risk of a pathological bone fracture at the resection level. The aim of this study is to evaluate the ultimate load on the femur with post-resection defect, taking into account the various elastic properties and toughness of bone tissue in different quadrants of the cross section of the bone. The elasticity modulus of bone tissue is determined using the nanoindentation test of the human femoral bone sample.

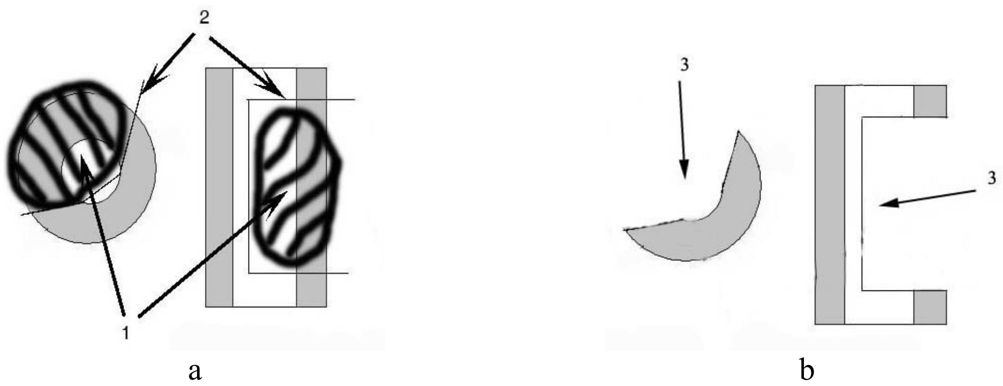


Fig. 1. Scheme of a surgical resection: (a) fragment of tubular bone before resection; (b) fragment of tubular bone after resection (1 - tumor, 2 – bone-cutting lines; 3 - post-resection defect)

## 2. Materials and methods

### *2.1. Nanoindentation of sample of bone tissue*

*Sample preparation.*

The sample for experiment was cut from the middle third of a human dry femor (male, 49 years, the sample was provided by the Republican Scientific and Practical Centre for Traumatology and Orthopedics, Minsk, Belarus). Grinding and polishing of bone specimens was performed according to the ANSI standard (grinding with paper