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GEOMETRICAL MODELING OF KNEE JOINT INCLUDING ANATOMIC PROPERTIES

Summary. Presently, CT is one of the most common and accessible methods of human internal structure research. Current programmes for tomographic data processing of data logged from tomography projection allow generation of three-dimensional images of organs. These reconstructions show that they are usually suitable for a precise preparation of surgical procedure operation planning, particularly in the case of joints. In the paper, basic methodology of that kind is shown on the example of a knee joint. The methodology leads to obtaining individual three dimensional models of large human joints. Analysis of tomographic data and creation of the three-dimensional model of the joint was conducted with use of MIMICS.

1. INTRODUCTION - ANATOMY OF THE KNEE JOINT

The knee joint plays a very important role in human locomotion. Its structure and time behavior during different types of motion show full adaptation of the knee to its required function. The knee joint is the largest and most heavily-loaded joint of human body. The knee involves the largest bones of the human skeleton – the tibia and femur. The patella is an important component of knee, especially in the extended position of the joint. The lateral and

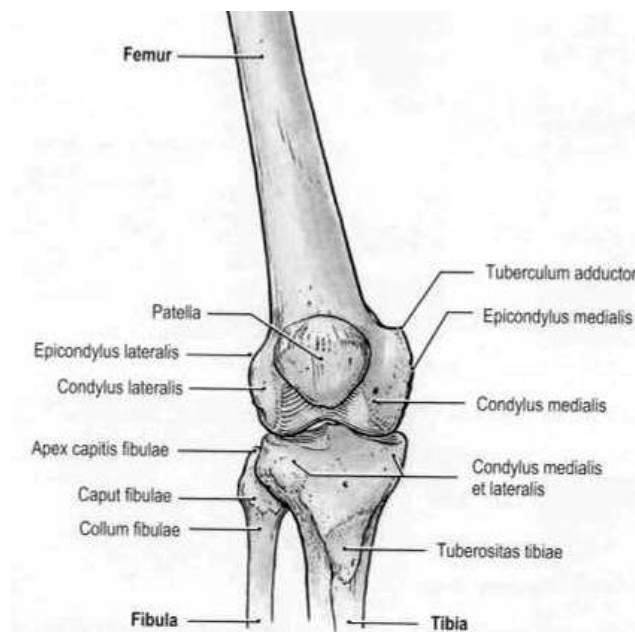


Fig.1. Bones of the knee joint [1]

medial meniscus constitute the articular surface of the tibia bone. The anatomical fitting of the articular surface to the articular capsule, along with the cruciate and patella ligaments, create the passive stabilizer system of the joint. Various muscles and their tendons form the knee's dynamic stabilizers (Fig.1.).

2. CT EXAMINATION

Computer tomography (CT) combines the basic rules of X-ray physics with mathematics, engineering and computer science. The spacial image of internal human body structures is gained by taking a sequence of layer-by-layer photographs (scans). Due to the fact that X – rays pose a relatively limited detriment to human tissues, CT is regarded as a non-invasive method. One of the advantages of CT is the possibility of fabricating three-dimensional models of human tissues after the three-dimensional image reconstruction [2,5]. In order to get data for geometrical modeling and obtain the important anatomical joint features, several computer X-ray tomograph projections are made in accordance with the methodology described in [6]. During data aquisition the patient is lying on their back with the limbs directed towards the detectors of the CT apparatus.

A specialized pillar was placed under the knees in order to cause a 30 degree bending. CT investigations were carried out by means of helical scans with 1,25 mm pitch and 1,375:1 ratio. The time of the individual scan projection was 1 s. Apparatus power conditions were 120 KV and 300 mA. The width of the beam was from 35 to 42 mm and covered both knee joints. The investigation was realized in four steps:

- 1) resting - in which 1/3 part of the distal femur und the tibia protuberance was covered,
- 2) during the conduction of the quadriceps muscle of thigh – in which the surface of patella-femur was covered,
- 3) internal rotation of the tibia – range as in point 2,
- 4) external rotation of the tibia – range as in point 2.

The approximate X-ray radiation exposure DLP in mGy-cm was calculated for the 30 mm thickness of the body phantom, and was from 1100 to 1500 mGy-cm according to the research range. Anatomical shaping of the knee joint is described by the angles and parameters [7], e.g.: the patella shape is estimated on the layers from the 1st stage of the research by using patella depth parameters and measuring Wiber's angle. Patella depth is measured as a multiplication of the maximum cross-section dimension measured to the surface joint edge. The maximal dimension was measured orthogonally from a designated patella equator to the lowest point of patella joint surface. This should be in the range of 3,6 – 4,2. Wiberg's angle is created by joint surfaces – bone one and medial one of the patella. For the right patella, this is in the range of 120 – 140 degree.

Another parameter that determines anatomical shaping is venue. It is derived from fitting the joint surfaces and the right strength of stabilizers. This results from the tendon strength and the right balance of muscular strength between lateral and medial head of quadriceps muscle. Joint venue is the condition of the angle value of intercondyles groove. This angle is created by the femur's condyle surfaces and is measured on the level going through the condyle with visualization of the intercondyles fossa. The angle value of the intercondyles groove should be between 125 – 143 degree.

Venue degree of the knee joint is estimated by the measurement of congruent angles and lateral patella measured in the stages of functional research. Congruent angle is the angle between the line leading from the lowest point of patella joint surface and the bisector line degree of intercondyles groove. The lateral angle according to Laurin'a is the angle between the line joining the front surfaces of femur bone and the line drawn along lateral contour of the patella joint

3. GEOMETRICAL MODELING OF THE KNEE JOINT

3.1. CT data analysis and surface model generation

As a result of CT projection, one obtains the sequence images that are cross-sections of bones and muscles of a patient's joints.

In order to get sharper images [3] of particular tissues, grey scale (from the black color for the low values of Hounsfield's coefficient to the white color for high value) is used. CT image processing is performed according to the following stages:

- 1) determination of CT coefficient in a range of interest that allows for the physical identification of the bone tissue,
- 2) segmentation of the images in the range of interest,
- 3) filtration of the chosen image range,
- 4) definition of the critical value for the proper contour interpretation and the ranges of analyzed edges,
- 5) contour detection and determination of discrete values of coordinate contour points,
- 6) data transforming (cloud of points) in order to support bone model generation and then surface model generation (Fig.2.).

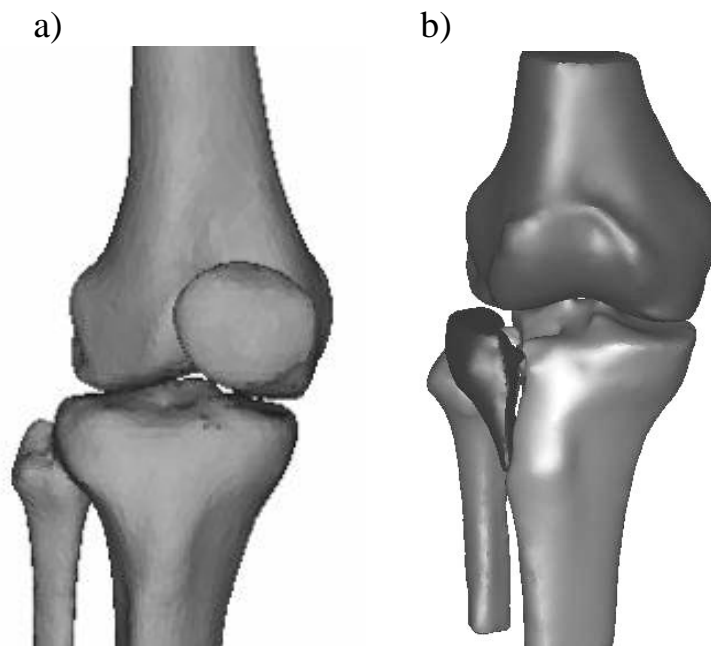


Fig.2. Surface model of knee joint: a) normal knee, b) fracture of proximal tibia bone

The object obtained by the above methodology is composed of triangular planes. Those planes are created from tomographic projections of the particular scans, which can be seen in the form of characteristic scans between particular scan layers. As a result, this process gives the undesired effect of sharp edges. This makes working with the model difficult. In order to reduce these effects, a correction has to be applied which consists in defining the triangular planes creating the object and densifying the mask of the edge.

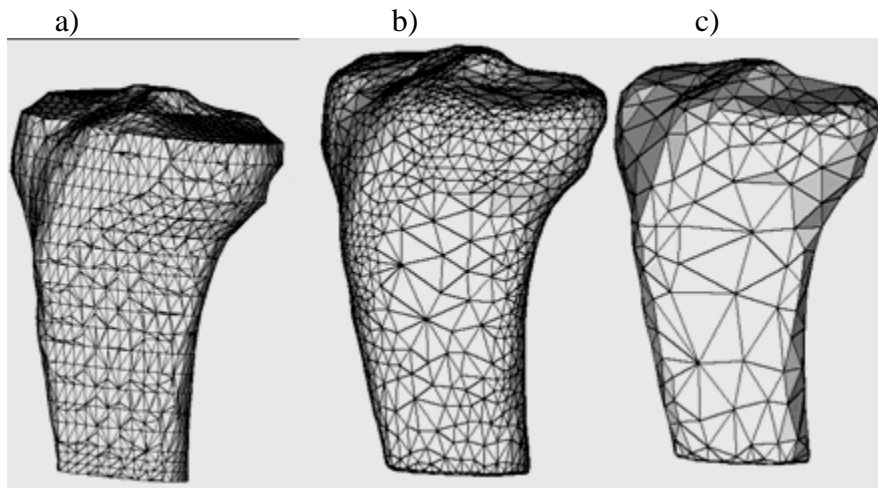


Fig.3. Different triangularizations of the proximal tibia model: a) initial model, b) model after correction, c) model with improper correction

The conducted correction yields a morphological simplification of model surface, including anatomical features such as protuberances or intercondyles eminence. Using the result of this operation, one can obtain a three-dimensional surface model of a specific knee joint (Fig.3.). It must be noted that virtual surface models of knee joints (normal and fracture) are also very useful in the pre-operative planning (Fig.4) of the surgical operation [4].

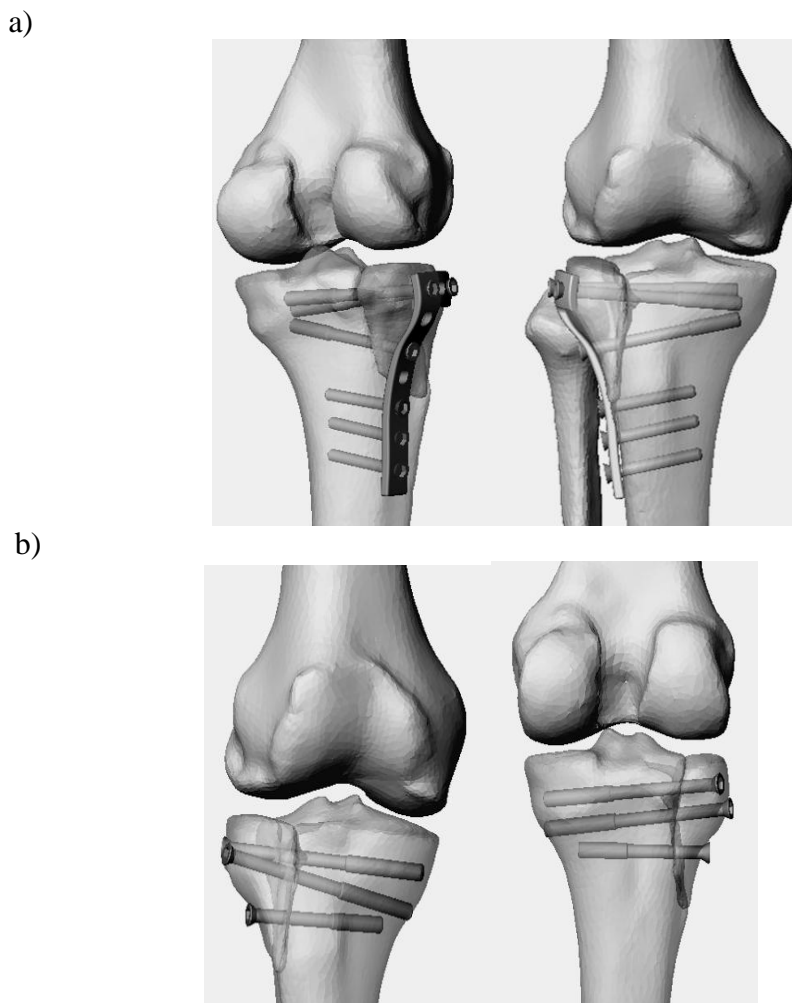


Fig.4 . Virtual operation planning of the tibia osteosynthesis: a) angle plate, b) screws

3.2. Non – homogenous model of joint knee bones

Bone density is the physical parameter that shows the changes in the bone structure. This parameter is a basic one presenting the changes in the bone structure after the endoprosthesoplasty. In order to obtain a non–homogenous model of the bone tissue, one has to complete the following steps on the model:

- generate a surface model,
- export to FEM program (ABAQUS),
- create a solid model and generate a finite element mesh (tetrahedral elements),
- import the model to MIMICS FEA program and determine the properties of bone tissue density.

Deriving a non-homogeneous model of knee joint bone (Fig5.) and attributing the proper tissue density to the particular model elements is done on the basis of tomographic data (CT). The density corresponds to the radiological density (HU) of each element, and is dependent on bone type (femur, tibia). The following equations relating radiological density d [kg/m^3] with bone tissue density were applied for the finite element analysis [8]:

- bone tissue density for femur,

$$d_f = 1.67 \cdot \text{HU} + 131 \quad (1)$$

- bone tissue density for tibia,

$$d_t = 0.916 \cdot \text{HU} + 114 \quad (2)$$

- bone tissue density for patella,

$$d_p = 0.916 \cdot \text{HU} + 114 \quad (3)$$

Finally, it is necessary to mention the highly-significant role that bone fracture modeling can play in reconstruction of the damaged and displaced articular surfaces of the knee joint.

As a result of this transformation, one can obtain a knee joint model composed of 10 – node finite elements (tetrahedral) in which it is possible to distinguish the boundary of cortical bone structure.

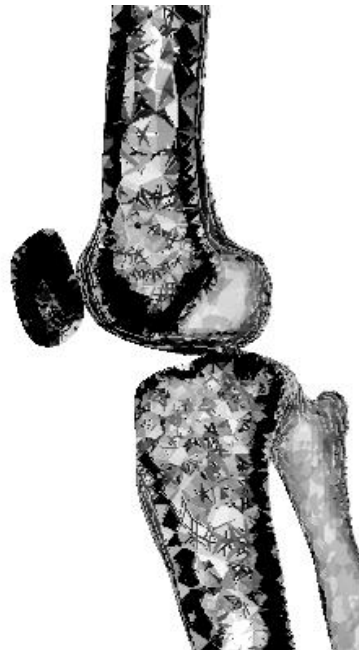


Fig.5. Section of non-homogenous structure of the femur and tibia model

4. RESUME

Computer tomography provides a possibility of useful and noninvasive reproduction of internal organs by geometrical modeling. Thanks to the sensitivity of the method, CT is well-suited to visualization and evaluation of bone system pathology.

Research using CT allows analysis of human body tissues in a non-invasive method. Its main advantage is the ability to obtain an image series that allows diagnosis of pathology. In this method the patient is minimally exposed to X-rays. In relation to the current programs for tomography data processing, one can produce three-dimensional models of human joints. The properly prepared model is the basis for future research by using FEM-type programs. It is also necessary to remember that the object obtained must be as accurate as possible with respect to its natural primary model. Therefore, during the process of model creation co-operation between a doctor and an engineer is indispensable.

Application of a non-homogenous model may allow for more precise analysis of the remodeling process taking place in the bone tissue. A deeper analysis should be applied to equations (1)-(3).

This paper is the beginning of a wider co-operation between doctors and engineers. The aim of the co-operation is to work out techniques for operation planning by use of the methods mentioned above. This will allow reduction of risks related to operations and improvement of post-operation results.

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