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Reverse engineering of human bones by using method of anatomical features

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ABSTRACT

In this paper a new method of anatomical features (MAF) for the creation of 3D geometrical models of human bones (polygonal, surface and solid) and parametric point models (predictive bone models) is presented. The main benefit of the MAF application comes from its capability to create a complete geometrical model even if a part of bone is missing or only a single X-ray image is available. The testing of MAF for twenty femur samples and ten tibia samples have shown that the created bone and bone region models are characterized by a good level of anatomical and morphometric accuracy, that is, they are within the required limits defined by orthopaedic surgeons.

1. Introduction

In contemporary medicine, the anatomically precise and morphologically correct 3D geometrical models of human bones are of outmost importance for the correct planning of orthopaedic surgeries and the creation of customized implants and fixators. There are two general approaches to the generation of 3D geometrical models of human bones.

The first approach is based on the generation of 3D geometrical models of bones belonging to a particular patient, on the basis of complete geometrical data gathered by using the medical imaging methods. Such images may be obtained by the volumetric scanning methods (Computer Tomography – CT or Magnetic Resonance Imaging – MRI) or by multiple 2D scanning (X-ray, ultrasound). This approach implies the generation of 3D geometrical models by using specialized software which forms an integral part of a medical scanner (e.g. Vitrea) or by subsequent processing of medical images in medically oriented CAD programmes (e.g. Materialise Mimics). One of the main disadvantages of such approach is the inability to generate the whole bone models in the cases when the medical images are incomplete or of poor quality due to osteoporosis, arthritis, tumour or a shattered bone. Sometimes a complete bone model can be created, but with big approximation of its shape, which considerably reduces model quality and its possible application.

The second approach to the generation of 3D geometrical models of bones or bone segments is based on the use of a predefined predictive model of bones and data acquired from medical images. With predictive models, the geometrical entities have been described by mathematical functions, the arguments of which are the morphometric parameters or some other legible parameters which can be read from medical images of a particular patient. Morphometric parameters are measurable dimensions, which can be acquired from medical images, for example CT or X-ray. Through such an approach, it is possible to generate the 3D geometrical model which best suits the physical model of a patient's bone, even in cases when only partial data about bone shape and geometry is available. The potential shortcomings of such an approach can be the insufficient number of parameters or the inadequately selected parameters.

In this paper the MAF which defines a new approach to the description of geometry of human bones based on the anatomical landmarks (e.g. Centre of Femoral Head) is presented. By using the MAF, it is possible to generate not only the 3D geometrical models (polygonal, surface and solid), but also parametric point models (predictive bone models).

The 3D geometrical models of bones have been created by using the Referential Geometrical Entities (RGE) described in [1] by Stojkovic et al. as the basis for the definition of bone 3D geometry (curves, polygons, surfaces). RGE represent the geometrical entities (points, lines, axes, planes) created in reference to the anatomical landmarks.

The parametric point model is a predictive model composed of parametric functions in which morphometric parameters have been used as arguments. Linear regression is used for the statistical analysis of geometrical data scanned from twenty femur and ten tibia samples, and for the creation of parametric functions. These functions describe relations between morphometric parameters and coordinates of points on the bone surface. Morphometric parameters are in relation, or referenced to the RGE and can be acquired from medical images.

The main aim of applying the MAF is to generate the 3D geometrical models of bones of high geometrical accuracy and anatomical precision, even in the cases when the image of a patient's bone is incomplete or only a single X-ray image is available for the acquisition of parameters values.

The models gained through the MAF could be used in the processes of planning/simulation of orthopaedic surgeries which have partially been described in [2] by Mitsuishi et al., or in bone cutting processes, presented in [2,3] by Mitsuishi et al.

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2. Related work

Medical images form a basic element of most methods applied to the generation of the 3D geometrical models of human bones. One of the most important steps in the processing of medical images is the segmentation, i.e. the process of segregation of anatomical entities in the medical image. The process of images segmentation can be performed by the semi-automatic approach presented in [4] by Mingchen et al., or by the automatic segmentation approach which is presented in [5] by Neeraj and Lalit. The images segmentation process is especially important with volumetric scanning methods, since the volumetric 3D model is generated on the basis of the individual segmented images with created 2D contours.

The generation of a 3D model of bones based on the defined 2D contours is a very complex process and it is automatically performed by applying the methods which have been presented in [6] by Hug et al. In general, all the methods applied in this process can be split into the methods by which the polygonal 3D model is generated on the basis of 2D contours (tilling) or indirectly, through the volumetric model generated over the 2D contours (isosurface). The given procedures have been presented and explained in the dissertation [7] by Zsemlye.

The first approach implies the creation of a polygon over the two consecutive contours by connecting the adequate anatomical points into the relevant polygon, whereby problems may arise in the selection of appropriate points. This approach has been partially presented in [7] by Zsemlye and [8] by Fuch et al.

The second method is based on the creation of the so-called binary masks, over which the polygonal model is created by using some of the algorithms such as marching cubes presented in [9] by Raman and Wenger.

The medical images segmentation is a process which very much depends on the quality of medical images and the preliminary knowledge of the object of scanning (necessary for the accurate connection of adequate anatomical points). Also, there are cases when the application of volumetric scanners is impossible due to the already mentioned reasons, so the scanning must be done by 2D devices, which makes the process of generating the volumetric models far more difficult.

The creation of predictive models provides solution of the mentioned problems, since it allows for the creation of models on the basis of the value of parameters which may be read from the incomplete CT or X-ray image. Typical examples of predictive models are the Statistical Shape Models described in [10] by Heimman et al. The Statistical Shape Models are generated on the basis of the input set of the bone models upon which some of the statistical methods have been applied.

The application of statistical models, multiple regression and quadric surfaces for femur geometry prediction has been presented in [11] by Sholukha et al. Some of the issues which may arise in the generation of predictive models are those related to the adequate selection of 3D entities which represent the anatomical regions of a bone. In that paper the application of quadric surfaces is presented, with which it is not possible to describe in detail the anatomy and morphology of a bone. Therefore their applicable value is considerably reduced in the cases where the higher accuracy of models is needed (for example Finite Element Analysis – FEA).

3. Materials and methods

3.1. Materials

The geometry analysis of the human bones in our research included twenty scans of femur samples and ten scans of tibia samples made by 64-slice CT (MSCT, Aquillion 64, Toshiba).

The samples came from Serbian citizens adults, intentionally including different genders and ages: nine female samples, both right and left, age 25–67, and eleven male samples, both right and left, age 22–72, of different heights and weights.

3.2. Methods

The idea guiding this research came out of the Point Distribution Method (PDM) applied for the definition and presentation of a cloud of points made over the training set of shapes. PDM has been explained in detail in the paper [12] by Cootes et al. Point distribution models applied in medicine rely on anatomically defined landmark points. An anatomical landmark point is a point defined by anatomists or surgeons on a specific human organ model for its every instance across the training set population. Examples of such points are the prominent points on condyles, the centre of the femoral head, etc.

The same authors suggest the application of Active Shape Model (ASM) for the description of morphological forms in medicine. By this method, it is possible to adjust the statistical model (PDM) created over the training set of shapes to the relevant new image gained by some of the medical imaging methods. The application of the ASM model has been presented in detail in [12] by Cootes et al. and in [13] by Kirschner et al.

By analysing the methods described in [4,5,7–9], it can be concluded that the majority of them is based on images segmentation and the definition of adequate anatomical points on boundaries segregating the anatomical entities. One of the potential problems with such approaches is the selection of anatomical landmark points in 2D images for the creation of segmentation contour. In order to successfully generate the model, it is necessary to select multiple points per image contour. These points can be the points of segmentation between the anatomical entities, or simply any ordinary points on the contour. Therefore, the number of points per contour can be different. The generation of models based on the curves in parallel planes not defined by the same number of points, or defined by the points not following the shape of anatomical entities, may lead to the reduction of the level of anatomical accuracy of the created model.

This paper introduces a MAF which is essentially a set of techniques and procedures aimed at creating anatomically precise and morphologically correct 3D geometrical models of human bones. MAF is based on the anatomical points defined on B-spline curves made over the 3D polygonal model in the CAD programme, as shown in Fig. 1c and d. In this way, the points have been defined on the bone model in the three-dimensional space as they would be defined in nature by the simple touch of probe onto the bone surface. The MAF comprises a large number of processes which can be generally split into the preparatory processes and the modelling processes.

The MAF preparatory processes have been shown (Fig. 1a) and explained in detail in [1] by Stojkovic et al. and they comprise: CT scanning part of the human body or dry samples (in this case the femur and the tibia); Image segmentation processes; Volumetric modelling and creation of the initial 3D human bone model; Model transformation into the STL format; Importing the model in STL format into CAD application and its further preprocessing.

At the end of the preparatory processing, the STL (mesh) model is created. This model represents input data for the geometrical model processing, which starts with tessellation and creation of the polygonal model. The next procedure is referential geometry defining – RGEs (planes, lines, axes, points and the like), which is defined on the polygonal human bone model in accordance with its anatomical and morphological features.

RGEs, presented in Fig. 1b, are used as the basis for the creation of geometrical entities. These entities are mostly spline curves and they are defined to closely fit the bone geometry and topology. At the end of the geometrical processing, anatomical points which define the boundary of certain anatomical regions on the polygonal model are created, as presented in Fig. 1c and d. The above procedure is repeated for each instance of the bone model from the training set.