3D Point Cloud Model of Human Bio Form Created by the Application of Geometric Morphometrics and Method of Anatomical Features: Human Tibia Example

Nikola Vitković[a], Ljiljana Radović[a], Miroslav Trajanović[a], Miodrag Manić[a]

[a]Faculty of Mechanical Engineering, University of Nis, Serbia

Abstract. Morphometrics refers to the quantitative analysis of a biological form and it can be used to describe its shape. Common types of geometric morphometrics are Landmark-based Geometric Morphometrics which describe shape by using anatomical landmarks (e.g. points), and Outline-based geometric morphometrics which uses envelope curves to describe shape of the biological form (e.g. bone), and they are not absolutely exclusive. Geometric morphometrics can be used for the creation of statistical models which represent shape variation of specific bio form. In this paper, novel application of geometric morphometrics for the creation of personalized models of unique bio-forms, i.e. models which are created for the specific patient is presented. Personalized model is defined as $3D$ point cloud model of biological form (in this case human tibia). Positions of points in $3D$ space are determined by using set of parametric functions defined by applying geometrical morphometrics, morphology properties and statistical analysis on the input set of human tibia samples. By using this technique, anatomically correct and geometrically accurate personalized models of bio forms can be created and used in pre, intra, and post-operative procedures in clinical practice.

1. Introduction

CAOS (Computer Assisted Orthopedic Surgery) is a scientific and technical discipline where computer technology is applied for the treatment of the patients in the field of orthopedic surgery. CAOS brings together various fields of science and technology, like medicine, engineering, mathematics, robotics, computer vision, information systems ect. [1, 3]. One of the elements which greatly influence on the outcome of applied CAOS procedures are accurate geometrical models of human bones. The geometrical accuracy, topological similarity, anatomical and morphological correctness of these models are required goals of every procedure applied for theirs creation. Also, such models enable creation of customized bone implants and fixators using additive and/or other manufacturing technologies [4, 5]. In order to create geometrical models which fulfill such requirements various methods are applied. These methods can be separated: by the type of model which they create, by the type of scanning device which is implemented for the acquisition of

medical (bone) data, or by the techniques which are implemented. In general, two types of models can be created and they are three-dimensional (volumetric) and two-dimensional. Volumetric models represent models which are defined in 3*D* space and they can be separated as boundary/surface (point cloud, wire-frame, polygonal, etc.) and solid models (various CAD models, Finite Element Analysis Models, etc.). They can be created by the application of various techniques (Direct modeling, Parametric modeling, etc.) which are generally known and presented in [6–12]. Accurate 3*D* models of human bones are in the majority of cases created on the basis of the geometrical data acquired from the three-dimensional medical scanning devices (like Computer Tomography CT, 3D Ultrasound), or on the basis of two or more 2*D* images from two-dimensional scanning devices (X-ray or Ultrasound) [8–13]. Possible shortcoming of this approach is the inability to create a model of complete bone in cases of missing bone data. e.g. bone illness like tumor or unavailability of the CT scanner. In such cases, predictive bone models can be used. Geometric entities of predictive models are described by parametric functions, whose arguments are morphometric parameters that can be acquired and measured from medical images. In order to create such models various statistical and numerical methods can be used as described in [7, 10–12]. Morphometric parameters are dimensional values which are defined in field of medical morphometrics and they are essential for the successful appli-cation of predictive models. The main goal of morphometrics is to analyze variation in bio form shapes and their covariance with other established properties (variables) [13–16]. Traditional morphometrics was defined at the beginning, and it enabled definition of linear distances between established landmarks used in multivariate statistical tolls, for the description of shape variation in the input set. This approach can also use counts, ratios, areas and angles measures on bio-forms. Two possible drawbacks of this method can be: loose connection with other important variables like height or width of the specimen included in the research; Locations of measurements were not initially defined, and that could produce equal results in measurement value; Graphical representation of the bio-form shape was practically impossible to create [13–16]. To overcome these issues geometric morphometrics technique was created. Two main methods were developed in this improved morphometric technique. Landmark-based geometric morphometrics was first method and it uses a set of landmarks (e.g. anatomical landmarks) to describe shape [16]. Land-mark is defined as a 2*D* or 3*D* point described by the established set of rules. The quality of the landmarks strongly influenced on the useful application of this method – each landmark also has to be present on every studied organism. If landmark cannot be defined on each specimen than it should be approximated. The main characteristics of the landmark morphometrics is that number of specimens should be equal to the number of landmark defined, because extra landmarks will be redundant. In general, there are three types of landmarks: true landmarks that are biologically important; pseudo-landmarks which are defined implicitly or relatively, e.g. the point on the curve that lies in the middle of the notch, semi-landmarks which are defined as relative to other landmarks, e.g. point at the relative location to the landmark A [15, 16]. As already stated, landmark based geometric morphometrics highly depends of the location and number of the landmarks, and because of that sometimes it is impossible to properly reconstruct shape of the bio-form. To overcome these problem, outline based morphometrics can be used. The main characteristic of this method is that it is used to describe outline configurations of the bio-shape, i.e. points are defined along boundaries of the shape. This method is not capable of capturing shape changes inside an object, but it can be used together with landmark morphometrics to overcome this issue [15]. This research extends and implements both morphometric techniques (landmark and outline) for the creation of the 3*D* parametric point cloud model for the specific bone or bone part, which can be personalized to the specific patient, by using morphometric parameters defined by traditional morphometrics, and in-house developed Method of Anatomical Features (MAF) [7, 10, 11]. Possibility to recreate missing part of the bone or to define plate implant shape before surgery is of great importance for CAOS, and for the patient successful recovery.

2. Developed method

The techniques presented in this research are part of the Method of Anatomical Features (MAF) which introduces a new approach to describe geometrical entities of human bones, and it enables creation of various geometrical models of the human bones. MAF method has already been presented in previous researches [7, 10, 11], but in this research method is revised, improved, and extended by the application of

novel techniques defined in this study. MAF is a complex method, and because of that, Structured Analysis and Design Technique (SADT) [17] is used for its the description. SADT diagrams are used for the graphical representation of system processes, and they enable detail analysis of system and involved resources. The main components of SADT diagrams are input elements, recourses, control elements, and output elements. In order to apply SADT on MAF, it was essential to define main components of the method. Analysis of MAF was performed and main components were defined as:

1. Input elements – labeled with capital I: Volumetric images of the patient (bone) created by CT or MRI; 2*D* images of the patient (bone) usually created by the application of X-ray.
2. Mechanisms (Resources) - labeled with capital M: Doctor – surgeon; Designer – Expert in CAD and medical software; Software packages: Materialise Mimics, CATIA
3. Control elements - labeled with capital C: Medical knowledge; Rules and limitations of applied methods in MAF; Morphometric rules – Rules about morphometric parameters;
4. Output elements - labeled with capital O: Geometrical models of human bones – polygonal, NURBS (surface), solid, models for Finite Eleventh Analysis (FEA), etc.
5. MAF contains basic and additional processes (Figure 2). Basic processes are presented in Figure 3 and additional processes are presented in Figure 4. Basic processes enable complete geometrical and anatomical definition of the specific human bone, and they are:
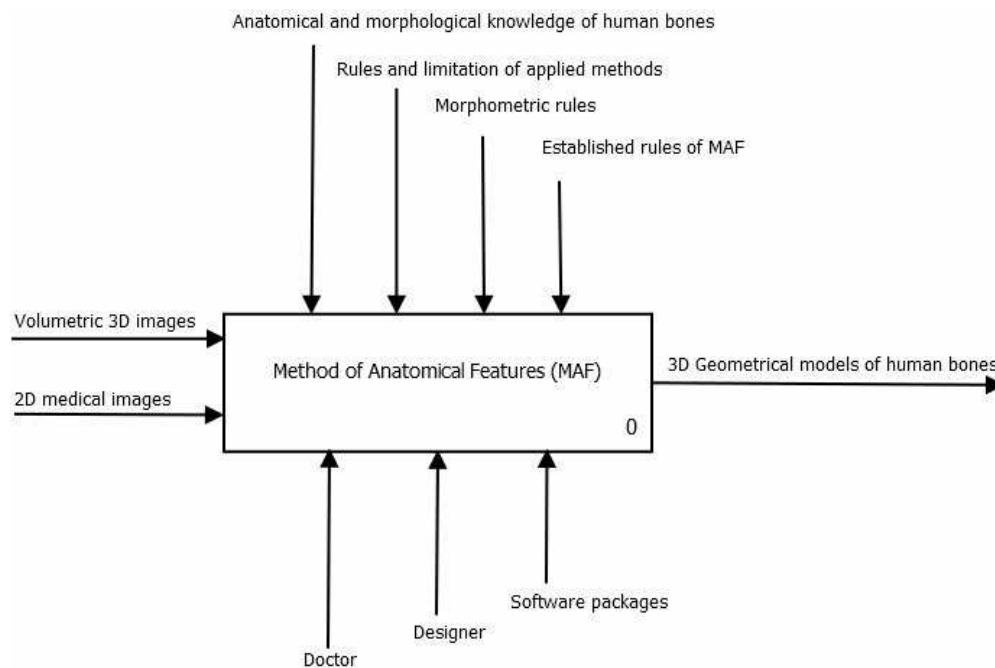

Figure 1: Basic components of MAF–A–0

- Creation of initial polygonal model (A11) – This process contains several procedures, which must be performed in sequential order: Scanning of human bone by the application of CT scanner; Segmentation of the acquired images, Forming of the polygonal model and its conversion to STL format - creation of the initial point cloud; Cleaning of the point cloud; Creation of the tessellation model; Additional processing of the tessellated model (filling holes, fixing irregularities in model
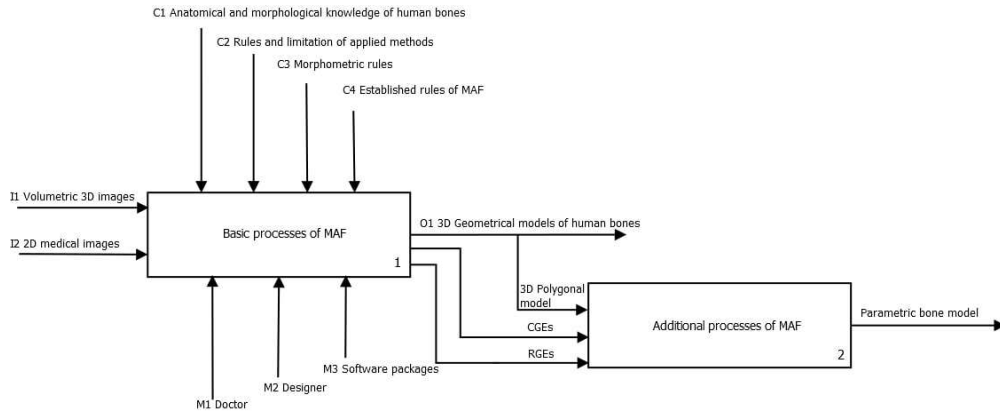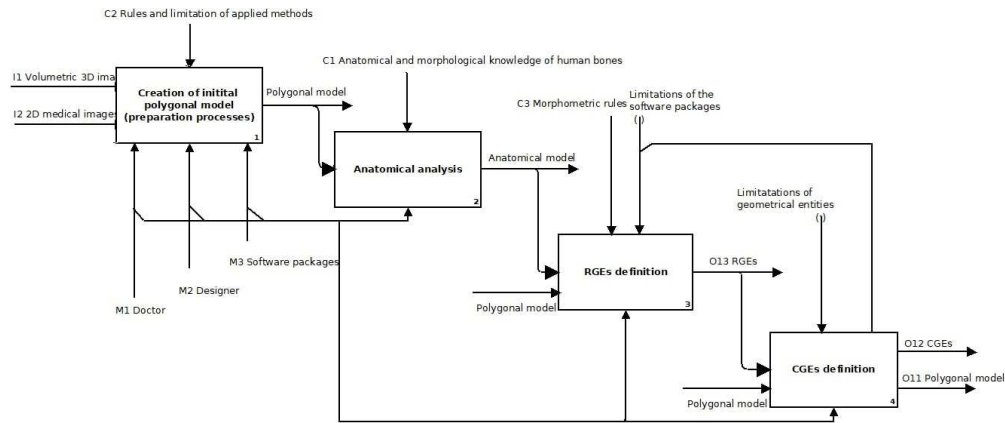
Figure 2: Basic components of MAF

Figure 3: Basic components of MAF–A–1

- Anatomical analysis (A12) – The process of anatomical analysis presumes anatomical and morphological analysis of the human bone in order to create anatomical model of the human bone. This model is a semantic model which connects geometrical elements on the polygonal bone model with anatomical and morphological terms, which are already defined in medical literature.

- Definition of Referential Geometrical Entities (RGEs) (A13) – RGEs are geometrical entities (points, lines, planes, axes, etc.) which are created on the polygonal model of the human bone. These entities represent basic geometry which is used for the creation of all other geometrical elements, e.g. surfaces.

- Creation of Constitutive Geometrical Entities (CGEs) (A14) – RGEs are the basis on which CGEs are created. These entities are called constitutive because they are used for the creation of surface and solid models of the human bones, and parts of the bones, in accordance with bone morphology.

Processes which are used for the creation of parametric bone model are called additional processes of MAF (Figure 4) and they are:

- Definition of parameters (A21) – First step in this process is to define morphometric parameters, which are clearly visible and measurable dimensions in medical images, and also defined in medical literature, and by traditional morphometrics. These parameters are defined individually for each human bone [9, 15].
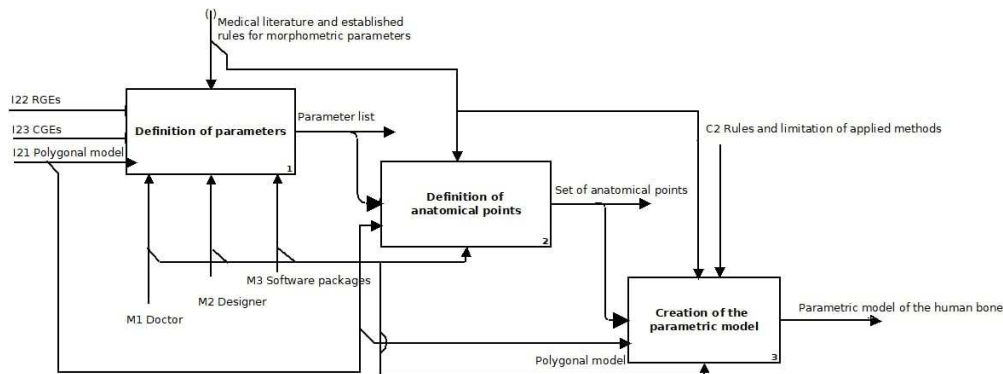
Figure 4: Basic components of MAF-A-2

- Definition of anatomical points (A22) – Anatomical points are defined on CGEs or other important anatomical landmarks (true, pseudo and semi landmarks) on polygonal model, in relation to anatomical model of specific human bone and defined morphometric properties. This set of anatomical points must be defined for each bone in an input set. It is important to note that landmark geometric morphometrics states that number of landmarks should correspond to the number of specimens, but in this research that is not the case, because, reversed principle is applied, i.e. landmark points are created on the CGEs which are geometric elements used to describe bone shape, and not on the bone itself.

- Creation of the parametric model (A23) – The last step in the parametric model definition is to measure coordinates of points and morphometric parameters for each created polygonal model in a set. Measured values are applied in statistical analysis, and as a result, parametric functions with morphometric parameters as arguments, are created. These functions define values for coordinates of anatomical points in relation to morphometric parameters. Each coordinate (X, Y and Z) of every anatomical point can be calculated by the application of parametric functions width input arguments defined as values of morphometric parameters measured for specific patient. In the first iteration of the MAF, multiple linear regression was chosen as statistical functions [18], but other statistical methods can be applied also.

3. Creation of point cloud model of human tibia and its anatomical sections

In this section, specific application of the procedure will be presented, together with RGEs, CGEs and geometrical models created for tibia bone.

3.1. Human tibia geometrical entities and models

After obtaining of polygonal model, recognizing and defining of RGEs [7, 10] is the following step in reverse modeling process. In the case of the tibia, one of the most important RGE is a mechanical axis, i.e. a line from the center of the tibia plateau (interspinous intercruciate midpoint) extending distally to the center of the tibia plafond [19, 20]. When the mechanical axis is determined, it is possible to position differently oriented planes which are in accordance with anatomy of tibia, and to create CGEs and different geometrical models.

3D Surface and solid models were created by using contour spline curves obtained by intersection of rotational planes (rotate about mechanical axis of tibia) and polygonal model [10]. These spline curves represent CGEs, and they were used as sections in multi-section surface feature of CATIA software.

3.2. The definition of parametric model and Region of Interests (RSIs)

In order to create parametric model of the whole tibia, input set of bone samples was analyzed as presented in [10], points were defined, and multilinear regression was applied. The applied multiregression alghoritm is defined in [18] and implemented in MATLAB (1):

$$X = [ones(size(p_1))p_1 \ p_2 \ p_3 \ p_4 \ldots p_n]; \quad A = X' * X; \quad B = A\backslash X' * Xcoord; \quad M = X * B;. \tag{1}$$

Xcoord – Vector of x coordinates defined for the input set cloud of point;
p_i – Morphometric parameters ($i = 1, \ldots, n$);
B – Coefficient Vector;
M – Vector of calculated values (multilinear regression).

The parametric model was already tested and results were more than promising [7, 10, 11] . Next step is to use landmark and outline morphometrics to define individual points which belong to different section of the tibia bone. In order to perform such a task, tibia point cloud model was separated into sections by using the interpolated splines which goes through the anatomical points (landmarks). This sections can be defined arbitrary, because division into sections can be done by following anatomical model definition as presented in [19, 20], or by using recommendations from surgeons and create anatomical Region of Specific Interests (RSIs), as presented in Figure 5.
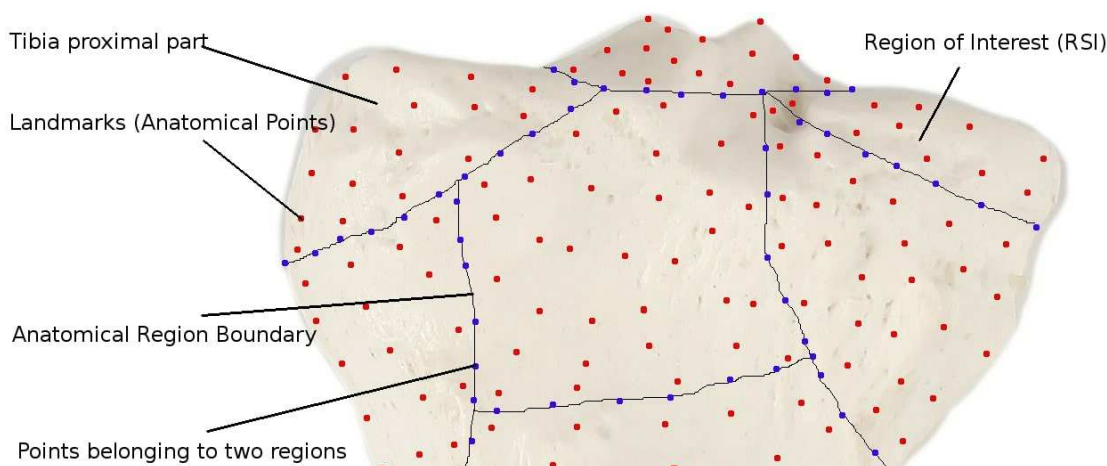

Figure 5: Definition of the anatomical landmarks and anatomical regions on the tibia proximal part

RSIs are very important for the preparation and for the performing the surgical intervention. For example if RSIs is defined as contact surface between bone and fixation plate, than surgeon can adapt plate shape (bend plate) to the patient bone before surgery, and therefore, shorten the surgery time and patient recovery. In order to define anatomical sections or RGIs input set of points was grouped into sets and defined as presented in (2).

$$AS_k = \{P_{k,1}, P_{k,2}, P_{k,3}, \ldots, P_{k,n}\}, \quad V = \{AS_1, \ AS_2, \ AS_3, \ldots AS_k\}, \tag{2}$$

AS_k is a kth–Anatomical section, $k = 1, \ldots, n$ (number of regions);
$P_{i,j}$ is a point in the kth anatomical section; V – Set of anatomical sections .

Interpolated spline curves were defined in such way that represent boundary between anatomical sections (3), which means that some points can belong to the more than one region (4) .

$$PS_z = \{P_{z,1}, P_{z,2}, \ldots, P_{zm}\}; \tag{3}$$

$$PS_{ci} \in (AS_v \cap AS_w), v, w = \text{indexes of the region}; \tag{4}$$

PS_z – Set of points belonging to individual spline, $z = 1, \dots , s$ (number of splines);
PS_{ci} – Set of anatomical points positioned on the boundary between regions.

Interpolated splines were defined as cubic splines (5). This means that $S3, n$ (x) cubic spline is defined as C^2 cubic piecewise polynomial of the third order, and therefore it can be defined as:

$$S_{3,n}(x) = \left\{ \begin{array}{ll} p_1(x) = a_1 + b_1 x + c_1 x^2 + d_1 x^3 & x \in [x_0, x_1] \\ p_2(x) = a_2 + b_2 x + c_2 x^2 + d_2 x^3 & x \in [x_1, x_2] \\ \vdots & \\ p_n(x) = a_n + b_n x + c_n x^2 + d_n x^3 & x \in [x_{n-1}, x_n] \end{array} \right\} \tag{5}$$

C^2 means that continuity of second and first derivate at any point in the defined interval is preserved, especially at the knots. To make this curves fully interpolated, one more condition must be met, and it is defined in (6) – function value, first and second derivate at the knot values should be the same.

$$S_{3,n}(X_i) = Y_i, \quad i = 1, 2, \dots , n; \quad p_i'(x_i) = p_{i+1}'(x_i) \quad p_i''(x_i) = p_{i+1}''(x_i) \quad i = 1, 2, \dots, n-1 \tag{6}$$

It is not just enough to mathematically define anatomical points, section and interpolated splines, yet, they need to be define in such way, that they can be used for the creation of patient specific point cloud. Anatomical points and defined anatomical sections are stored in relation database formed on MySQL server. For the creation of interpolated splines SCiPy library for Python was used. Therefore, procedure for creating patient specific point cloud with formed anatomical regions or RSIs was defined as follows:

Acquiring values of morphometric parameters form medical images by using adequate medical or image processing software; Applying these values in parametric functions and creating patient specific cloud of point by using python libraries; Forming anatomical regions by applying defined sets (point indexes) in database; Creating interpolated spline curves by using python libraries and calculated points; Forming RSIs point of cloud models; Transforming RSIs models into appropriate geometrical model (surface or solid) by using standard CAD techniques. In order to demonstrate defined procedure, creation of one RSIs with spline boundary is presented in Figure 6. Defined RSIs is a region on the bone which is used for the customization of the contact surface of the plate fixation implant by Mitkovic [26]. Defined surface can be used for bending fixator plate before surgery and adopting its shape to the bone form in the affected area. Boundaries of the affected bone area are defined by interpolating spline (e.g. fracture), Figure 6.
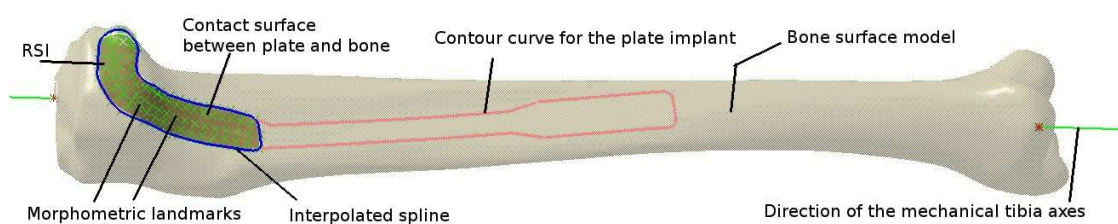

Figure 6: RSIs shown together with the bone surface model

4. Conclusion

In this paper, improved Method of Anatomical Features (MAF) was presented. This method is improved by adding rules applied in geometric morphometrics, and by introducing new Constitutive Geometric Entities (CGEs) for the definition of bone 3D models. These improvements enable creation of more realistic, geometrically accurate, and anatomically correct 3D models of the human bones. 3D models of human bio-forms created in this way can be used for: pre-operative planning, surgical guidance, production

of personalized plate implants and fixators, and educational purposes in medical science. One more improvement should be clearly stated and that is definition of the Region of Interests (RSIs). RSIs are defined on the point cloud bone model and they can help surgeon to reconstruct bone surface during preoperative planning processes in different area of the bone affected by bone illness or fracture, which can improve outcome of the following surgical procedure. It is important to note that application of MAF is not restricted to the human bones only, but it can be extended to other bio-forms, like soft tissue. The main challenge in the future research would be application of MAF for the development of the geometrical models of the human soft tissue. If created, these models will enable better preoperative planning in orthopedics and other branches of surgery, and automatic or semi-automatic creation of geometrical models of human organs and their anatomical sections.

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