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PROCEDURE FOR THE CREATION OF COMPLEX FREE-FORM HUMAN BONES SURFACES FOR MANUFACTURING OF PERSONALIZED IMPLANTS

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Abstract. Development of new and improvement of existent methods for creating geometrical models of human bones is a continuous process in modern medicine. The various methods are applied for the bone remodeling and creation of anatomically correct and geometrically accurate bone models. The main goal of this research is to improve process of bone surface reconstruction, by using enchanted Method of Anatomical Features (MAF). The MAF was improved by using novel approach for creation of Region of Interests, based on the application of Uniform Mesh, NURBS and SubD. Result of this improvement is a created procedure for the creation of individual Regions of Interest (ROI), combined ROI, or custom defined ROI, defined by medical case/physician requirements. The resulting surface model(s) can be used for manufacturing of personalized implants and/or preoperative planning.

Keywords: MAF, Surface, Implants, Manufacturing.

1 Introduction

Development of new and improvement of existent methods for creating geometrical models of human bones is a continuous process in modern medicine. Basically, most methods use medical images obtained from various devices (medical scanners) as input data. These devices can be classified into those which enable forming of 2D images of scanned object, such as X-ray or 2D ultrasound, and those which enable creation of 3D images (volumetric models), such as Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). Different types of processing can be performed on obtained data, resulting in adequate geometrical human bone models. Processing techniques are explained in detail in [1,2], and they can be generally divided on ones which uses complete bone data from medical images, and others which uses incomplete bone data. The procedures for creating bone models differ for both cases, and in a first case classical reverse modeling procedures are applied, while for other parametric or template models are generally used. Both methods can produce geometrical models of different quality, related to geometrical accuracy and anatomical and topological correctness. The quality

of models is generally influenced by the quality and amount of the input medical data and applied method for model regeneration, but also on the possible models application [1-3], which can be diverse: preparation and simulation of orthopedic interventions, conducting training to perform orthopedic interventions, production of osteo-fixational material, analysis of stress and strain of assembly of bones and implants. It is clear that in some cases, geometrical accuracy and anatomical correctness must be high (e.g. for Dynamic Compression Plates - DCP plates), but for some of the others it is not the case (e.g. presentation or learning models). In this paper, enchanted Method of Anatomical Features (MAF) [4], which combines different methods for creation of bone 3D geometrical models is applied for the reconstruction of specific bone regions, by using novel approach based on Nurbs and SubD [5] patching techniques. Initially created by the authors of this research, MAF method is already proven and verified in many applications [1,6]. During the development of MAF, it was noticed, that in the process of reconstruction of the bone surface, it is not always required to provide complete model of the bone, thus, sometimes it is enough create just surface model of some important part (e.g. connecting surface between plate implant and bone), and this individual parts were named RGIs [4]. Considering that the widely accepted acronym for the Regions of Interest is ROI, and that is usually used in medical imaging for defining anatomical sections, in this paper, that acronym will be used, but it refers specifically to anatomical-geometrical sections, as described in [4]. The main goal of this research is to improve process of bone surface reconstruction, by using already formed ROI, and novel developed remodeling techniques presented in this paper. Result of this improvement is a created procedure for the creation of individual ROI, combined ROI, or custom defined ROI, defined by medical case/physician requirements. These types of models can be used for preoperative planning and for the manufacturing of the personalized implants, such are bone implants (scaffolds), and plate implants. Besides presentation of surface creation process, procedure for the application of such surface models is proposed and described. This procedure will enable creation of surface models based on the physician requirements and use of that model as input models for preoperative planning and/or manufacturing processes.

2 The definition of parametric model and Regions of Interest (ROI)

To create parametric model of the specific human bone, input set of bone samples was analyzed, parameters and point cloud model was defined, and multilinear regression was applied, as presented in [2,6]. The output of the applied process is set of parametric functions which define correlation between bone morphometric and geometric parameters, and coordinates of points from point cloud. The parametric model was already tested, and results were more than promising [6]. To provide better control of morphology and geometry of the formed Parametric bone 3D Point Cloud model (PPC), further steps were performed and described in [4]. The main step was creation of ROI, which were defined as point sets, formed by selecting specific points from the PPC model, from different regions of the bone surface. To define these sets, landmark and outline

morphometrics, and also bone anatomy and morphology were applied [7,8]. To geometrically define ROI, point cloud model was separated into sections by using the interpolated splines which goes through the anatomical points (landmarks), as presented in Fig. 1 for the tibia bone. These sections can be defined arbitrary, because division into sections can be done as already stated, or by using recommendations from physicians and create Regions of Specific Interest (ROSI), with manually selected points from different predefined regions. ROI and ROSI are important for the preparation and performing the surgical intervention, because they allow better insight into bone shape and geometry, and position of the implants and plates. Mathematically, ROI were defined as mathematical sets, presented in (1).

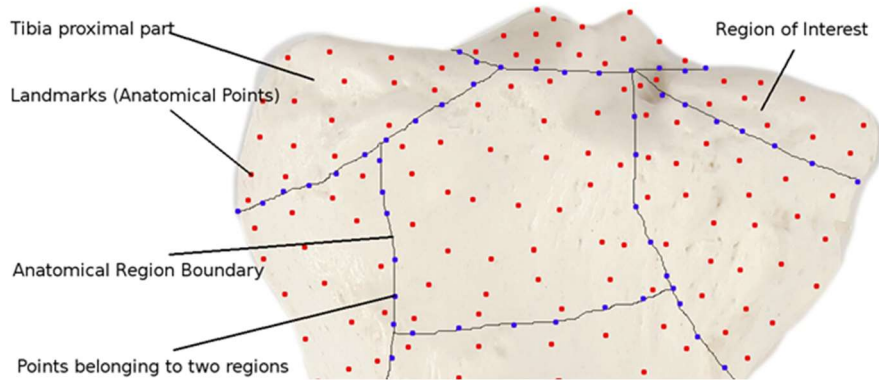


Fig. 1. Definition of the Region of Interest (ROI) on the tibia proximal part

$$AS_k = \{P_{k,1}, P_{k,2}, P_{k,3}, \dots, P_{k,n}\} \quad (1)$$

$V = \{AS_1, AS_2, AS_3, \dots, AS_k\}$, AS_k – K th – Anatomical section, $k = 1, \dots, n$ (number of regions)

$P_{i,j}$ – Point in the K th anatomical section; V – Set of anatomical sections

Interpolated spline curves were defined in such way that represent boundary between anatomical sections (2), which means that some points can belong to the more than one region (3).

$$PS_z = \{P_{z,1}, P_{z,2}, \dots, P_{z,m}\} \quad (2)$$

$$P_{Sci} \in (AS_v \cap AS_w) \quad (3)$$

where,

v, w = indexes of the region

PS_z – Set of points belonging to individual spline, $z = 1, \dots, s$ (number of splines)

P_{Sci} – Set of anatomical points positioned on the boundary between regions

Interpolated splines were defined as cubic splines (4). This means that $S_{3,n}(x)$ cubic spline is defined as C2 cubic piecewise polynomial of the third order, and therefore it can be defined as:

$$S_{3,n}(x) = \left\{ \begin{array}{ll} p_1(x) = a_1 + b_1x + c_1x^2 + d_1x^3 & x \in [x_0, x_1] \\ p_2(x) = a_2 + b_2x + c_2x^2 + d_2x^3 & x \in [x_1, x_2] \\ \vdots & \\ p_n(x) = a_n + b_nx + c_nx^2 + d_nx^3 & x \in [x_{n-1}, x_n] \end{array} \right\} \quad (4)$$

C2 means that continuity of second and first derivate at any point in the defined interval is preserved, especially at the knots. To make these curves fully interpolated, one more condition must be met, and it is defined in (5) – function value, first and second derivate at the knot values should be the same.

$$S_{3,n}(X_i) = Y_i, i = 1, 2, \dots, n; p'_i(x_i) = p'_{i+1}(x_i), p''_i(x_i) = p''_{i+1}(x_i) \quad (5)$$

$$i = 1, 2, \dots, n - 1$$

It is not just enough to mathematically define anatomical points, section and interpolated splines. They need to be defined in such way, that they can be used for the creation of patient specific point cloud and surface model.

3 Procedure Definition

The main procedure for surface forming is presented by using the flowchart diagram in Fig. 2. First step and most important is proper requirements definition. Requirements define resulting ROI and ROSI model(s) geometrical accuracy and anatomical correctness. It is already stated that ROI are predefined sets of anatomical and geometrical points, separated by defined boundaries, so how they will be used is defined in requirements definition process. Four main use cases are already defined:

- UC1. Strict application of predefined unique ROI
- UC2. Combination of more than one ROI by defining specific surface connection rules.
- UC3. Customized ROSI definition.
- UC4. Specific requirements concerning surface curvature and tangency in specific areas of ROI or ROSI.

First use case is the easiest to accomplish, because the points are already properly defined to create surface of continuous curvature and tangency. Second use case has more complexity because it is generally known that connection between predefined surfaces can be hard to accomplish if there is a possibility of creating only contact connection (point by point or by connection curve), not a curvature continuity. In this case the proposed algorithm should provide possibility to connect individual ROI by establishing curvature continuity through connection curve, by using NURBS or by using SubD surfaces [9]. The radius defined in each point, can be continual and resulting

surface will be topologically correct, which is the one of defined goals. Third use case is oriented to define custom ROSI by selecting individual points in different regions, which can be observed as specific ROI. The points are selected by using CATIA grouped features, which means that individual cloud points regions, or just particular points can be selected and validated, and then merged into one customized point cloud (ROSI). The process of defining points or points group is manual by using technical elements for selection (CATIA Feature – selection by polygon, spline, etc.). The same rules apply here as for the use case one, and the addition is a manual point selection. The last predefined use case is formed due to the requirements of different manufacturing technologies, and shape of standard and personalized implants.

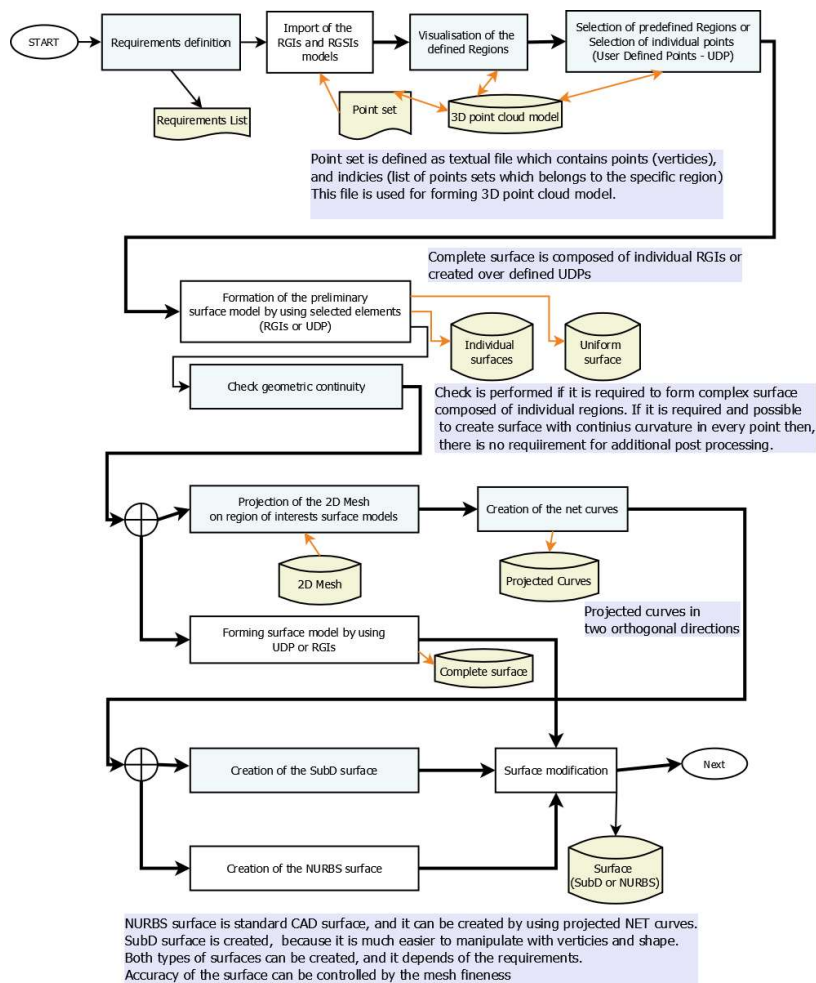


Fig. 2. Definition of the Region of interest (ROI) on the tibia proximal part

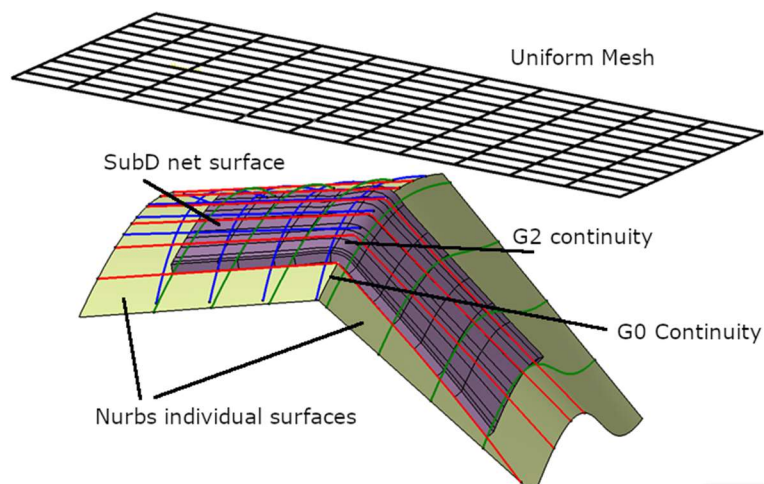
For example, suppose it is required to create custom titanium implant using high speed milling. In that case, it is important to enable proper movement of the tool, which cannot be conducted if surface is of non-uniform curvature. Also, if it is required to align ROI surface with known plate implant surface, with small deviation tolerance, then it is important to define accuracy requirements. The algorithm, or process definition presented in Fig 2. should provide proper outputs to each of the defined use case situation.

After the requirements were defined, and use case is preselected, the next step is to visualize the ROI or, to better say, display the 3D model. In this stage of the research CATIA is used as a tool for the algorithm testing. The 3D point cloud model is presented to the user, and regions boundaries are visible. The user selects regions, or selects individual points, i.e., User Defined Points (UDP) for ROI. The user then defines the special conditions, like connectivity of individual regions from UC2, or specific requirements concerning UC4. After that, user can use CATIA technical elements and create surface models of ROI, or chose creation by using automatic procedure defined by algorithm (which uses selected ROI points, or UDP to create mesh, and after that automatic surface creation with default parameters). For every created surface curvature continuity is checked, and if it is not proper, it is possible to correct it manually, by selecting additional point or removing existing points. Process defined as “Check Geometric continuity” means that, it is necessary to see if curvature connection between individual ROI can be established by using classical NURBS patch, or additional processing and application of uniform mesh surfaces is required. For the uniform surface composed of 3D points this can be achieved without using uniform mesh, because curvature is manipulated by surface parameters (classic NURBS surface creation) and included points. The problem arises when there is a requirement to connect two or more individual surfaces into one and enable smooth transitions with continual curvature. In such cases we propose application of uniform mesh with parametrically defined quads dimension (Fig. 3). The application of this mesh is the one of the most important parts of presented algorithm used for controlling bone surface geometry. The uniform 2D mesh is projected onto the created surfaces, and curves are created in u and v direction. The distance between points (mesh quad size) in u and v direction defines the accuracy of the created surface, i.e. smaller distance, more projected points. In Fig. 3a example of mesh implementation is presented. Two ROI are shown, and they are connected by using 3D spline curve without fillet (radius). The two ROI are defined as such in point cloud definition file, and that is expected behavior. To properly connect them, two approaches were used.

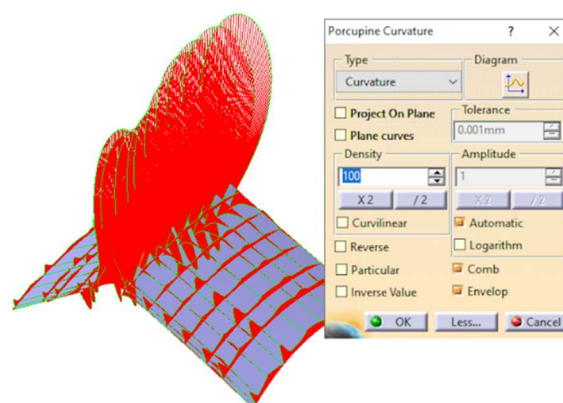
- First, uniform mesh is used, and projected on both surfaces. Projected points are connected to form 3D spline curves, which are used as the basis for the creation of net SubD surface. To control created surface, it is possible to do following:
- Set quad dimensions – Two parameters are defined and they are Width and Height of quad.
- Set number of curves in u and v direction – This parameter is arbitrary, and it generally depends on a complexity of surface shape.

- Control type of created spline curves – Cubic splines (B - Splines) can be used. It is important to mention, that we are not limited to the spline curves, other types of curves can also be used. It all depends on the requirements and resulting shape and accuracy.
- Create SubD surface by only using projected points and not curves – This parameter allows using only points as SubD initial point cloud base for forming deformable surface.

These four parameters are entirely enough to control SubD surface (Fig 3b). After the surface creation, it must be noted that it is possible to manually modify SubD surface by using Mesh tools, Face Subdivision, Face Cutting, and other available features [10]. As it can be seen of Fig. 3b, curvature is continuous in value, but it can be controlled, and processed by using previously defined features of SubD, if there is a requirement for additional modification.



a) Created surfaces by using uniform mesh



b) Procupine analysis of surface curvature

Fig. 3 Creation of connecting surface by using uniform mesh and NURBS and SubD surfaces

The second approach presumes application of NURBS patch, by using defined points in each region. Immediately, a problem arises, because the number of points in each defined region close to the border is not enough to control the connection between ROI. We only have points that define connecting the 3D spline curve. In some cases, when there is no requirement for accuracy, this can be acceptable, but if high control is required, then additional manual work must be done, or mesh can be used.

Nevertheless, a NURBS surface is created and presented in Fig. 4. Fig. 4a presents individual meshes created over ROI points, with G0 continuity. Fig. 4b presents merged meshes, with insufficient points in the connected area, and non-complete G2 continuity, and in Fig. 4c, a surface patch created by CATIA feature by using merged mesh with G2 continuity analysis, is shown. CATIA engine produced a valid surface patch, but geometrical and topological control is limited to the automatic patch feature capabilities, and usually, that is not enough for any serious manufacturing processes or accurate design, yet it can be used as a fast method for creation of presentation models. Of course, if splines are created manually through ROI, and additional points and curves are added, better control can be established, but that represents a classical modeling procedure, which can be avoided by using the proposed approach.

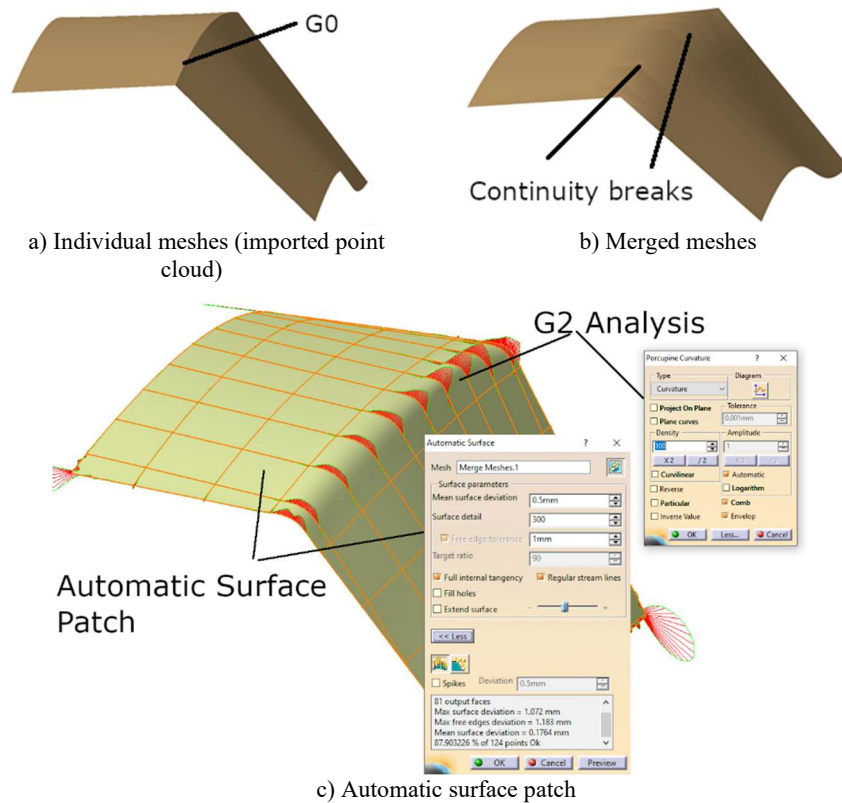


Fig. 4. Automatic merged surface creation by using CATIA technical features

4 Application of models for implants manufacturing

The possible application of bone models for implant manufacturing is presented in Fig 5. As it can be seen, the model can be used for the: Creation of personalized plate implants by using additive technologies (FFF, DMLS or EBM); Creation of rapid tooling processes (master pattern or direct tooling) for molds production; Using high-speed milling for mold production, Forging, etc.

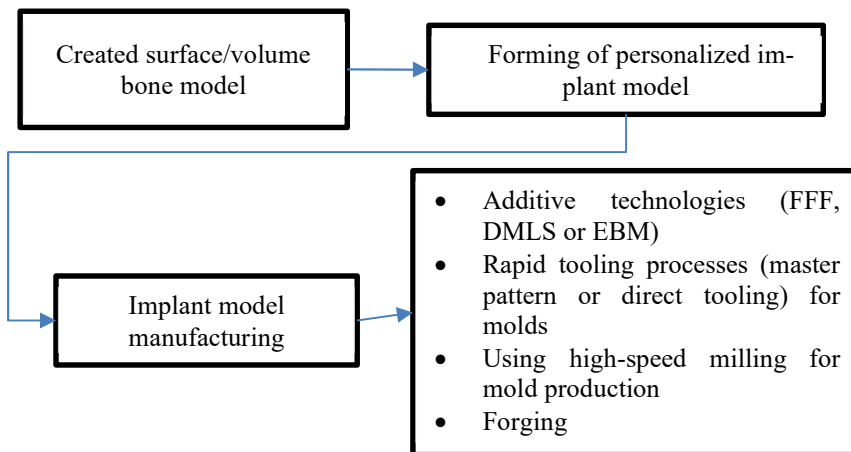


Fig. 5 Application of bone model for manufacturing

The one example for creating CAD/CAM model for FFF printing of Mitković¹-type plate implant/fixator, for presentation purposes is shown in Fig. 6. The initial polygonal model was obtained from CT images of patients using appropriate techniques, described in [1, 2, 11]: CT scanning, Preprocessing, Importing into CATIA and Filtering (removing points) CATIA. The initial model [11] was created by simple surface extraction from imported tibia bone, and as it can be seen in Fig. 6a, there is a non-curvature connection between proximal part and shaft, which can represent a problem for further manufacturing, as it is already stated. In this case, regions were defined and used, as combination of points from both proximal and shaft regions, Fig. 6b. The regions were defined, based on the outer boundary curve of fixator (plate), Fig. 6a, and used as input for the plate-bone contact surface creation. Plate-bone contact surface model is a classic example of ROSI, because points were manually defined/selected from different regions of already created tibia point cloud model [2, 6]. At the end, ROSI surface model was created by using sections of merged surface of tibia proximal part and part of the tibia shaft, limited by the boundary plate curve. The final model for CAM was created by using technical features of CATIA, like extrusion, revolves, holes, etc. (Fig. 6c). This model can be manufactured by different technologies, but in this case the easiest solution is to perform 3D printing/FFF. It is possible to print it together with a bone

¹ <http://www.mitkovic.org/>

model, to provide presentation of implant positioning, insertion, or bone-implant assembly procedure, to the students or medical practitioners.

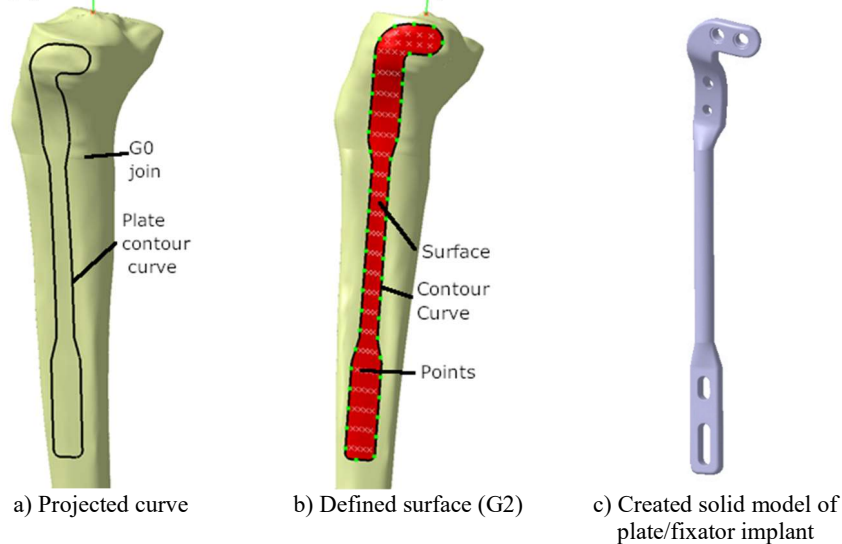


Fig 6. The procedure for plate implant model creation for CAM

5 Conclusion

In this paper, enchanted Method of Anatomical Features (MAF) is presented. The improvements are based on the novel methods for the creation of Regions of Interest (ROI) and Regions of Specific Interest (ROSI), by using uniform mesh, NURBS and SubD elements. These improvements enable creation of more realistic, geometrically accurate, and anatomically correct 3D models of the human bones, which can be used for: pre-operative planning, surgical guidance, production of personalized plate implants and fixators, and educational purposes in medical science.

ROI are defined on the point cloud bone model. They can help physicians reconstruct bone surface during preoperative planning processes, in different areas of the bone affected by bone illness or fracture, which can improve the 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 future research would be the application of MAF to develop the geometrical models of the human soft tissue by using ROI and ROSI. These adaptable models will enable better preoperative planning in orthopedics, and automatic or semi-automatic creation of geometrical models of all human body parts, not just bones, enabling better manufacturing processes in personalized medicine.

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References

1. Filippi, S, Motyl, B., Bandera, C.: Analysis of existing methods for 3D modelling of femurs starting from two orthogonal images and development of a script commercial software package, *Computer methods and programs in biomedicine* 89(1), 76–82 (2013).
2. Majstorovic, V., Trajanovic, M., Vitkovic, N., Stojkovic, M.: Reverse engineering of human bones by using method of anatomical features, *CIRP Annals - Manufacturing Technology*, 62(1), 167–170 (2013).
3. Cheng, Q., Liu, P. X., Lai, P., Xu, S., Zou, Y.: A novel haptic interactive approach to simulation of surgery cutting based on mesh and meshless models, *Journal of Healthcare Engineering*, vol. 2018, Article ID 9204949, 16 pages (2018).
4. Vitkovic, N., Radovic, Lj., Trajanovic, M., Manic, M.: 3D Point Cloud Model of Human Bio Form Created by the Application of Geometric Morphometrics and Method of Anatomical Features: Human Tibia Example, *Filomat*, 33(4), 1217-1225 (2019).
5. Catmull, E., Clark, J.: Recursively generated B-spline surfaces on arbitrary topological meshes, *Computer-Aided Design*. 10(6) 350-355 (1978).
6. Vitkovic, V., Mladenovic, S., Trifunovic, M., Zdravkovic, M., Manic, M., Trajanovic, M., Mistic, D., Mitic, J.: Software Framework for the Creation and Application of Personalized Bone and Plate Implant Geometrical Models, *Journal of Healthcare Engineering, HINDAWI LTD*, vol. 2018, Article ID 6025935, 11 pages (2018).
7. Klingenberg, C. P.: Size, shape, and form: concepts of allometry, *Dev Genes Evol*, 226 (3) 113–137 (2016).
8. Mitteroecker, P., Gunz, P.: Advances in Geometric Morphometrics, *Evol Biol* 36, 235–247 (2009).
9. Shen, J., Kosinka, J., Sabin, A.M., Dodgson, A.N.: Conversion of trimmed NURBS surfaces to Catmull–Clark subdivision surfaces, *Computer Aided Geometric Design*, 31(7–8), 486-498 (2014)
10. Kovacs D., Mitchell, J., Drone, S., Zorin, D.: Real-Time Creased Approximate Subdivision Surfaces with Displacements, *IEEE Transactions on Visualization and Computer Graphics*, 16(5), 742-751 (2010).
11. Vitković, N., Mitković, M.M., Mitković, B.M., Korunović, N., Stevanović, D., Veselinović, M.: Reverse engineering of the mitkovic type internal fixator for lateral tibial plateau, *Facta Universitatis, Series: Mechanical Engineering*, 13(3), 259-268 (2015)