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Novel design approach for the creation of 3D geometrical model of personalized bone scaffold

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ABSTRACT

Bone scaffolds provide a structural support for tissue development. Existing bone scaffolds are mainly characterized by complex porous designs whose shortcomings are a low level of permeability for growing tissue, and a difficult design customization. Scaffolds with nucleuses (rods or lattices) as basic elements should improve bone regeneration and enable higher design flexibility. In this paper, we present two new methods for building 3D geometrical models of personalized scaffolds, which are based on method of anatomical features. Methods are demonstrated in the case of scaffold for the mandible bone. This approach greatly reduces the designer effort and time, while enabling easy personalization of scaffolds' shape and geometry.

1. Introduction

Human bones can be subjected to different traumas, like fractures, diseases, and infections. If there is a requirement to restore the bone tissue at the place of trauma, bone grafts can be used. Currently, three general types of grafts are used in clinical practice: autographs (the tissue is acquired from the same patient), allographs (the bone tissue is acquired from a living or deceased donor) and bone graph substitutes [1,2]. Autographs and allographs are commonly used and their characteristics are well documented [1–3]. Bone graph substitutes are the product of Tissue Engineering (TE) application, which focuses on developing the replacement tissue by using the patient's own cells, grow factors and scaffolds [4]. Scaffolds are porous synthetic 3D structures which enable the growth of new bone tissue at a place of bone trauma. In order to enable proper tissue development, scaffolds ideally should be biocompatible, and biodegradable, adhesive (to enable cell attachment), highly porous (to enable better cell feeding and distribution through scaffold structure), mechanically strong (to provide support for growing tissue, and to sustain load) [1,2]. To fulfil stated requirements, various design concepts for the creation of scaffold are currently applied. Beside the stated general requirements, parameters like surface-area-to-volume-ratio [5], stiffness, manufacturability, and material [1] can have great influence on the complexity of scaffold architecture, and can possibly prevent easy personalization of scaffold design to a specific patient [1–7]. Typical design concepts are:

- Unit cell design concept [5,6] — Scaffold architecture is defined by multiplication of unit cells throughout the volume which should be replaced by the scaffold.
- Image based design [7] — Image-based design techniques use CT scans [8] for the design of 3D scaffold architecture with various porous structures.
- Implicit surfaces modelling [9] — Implicit surfaces modelling is an adaptable technique which enables creation of scaffold architecture by using mathematical modelling.

For the purpose of improving scaffold design, two novel scaffold design methods based on the Method of Anatomical Features (MAF) [10–12], were developed and presented in this paper.

Both methods are founded on the application of parametrically defined nucleus elements used for the creation of 3D scaffold architecture. These methods improve scaffold design concerning specific bone geometry and morphology (personalized scaffold), overall scaffold architecture, material selection and manufacturing of scaffold. This means that parametrical design of the scaffold model enables creation of scaffold architecture which can be easily adapted to the requirements of a specific medical case.

2. Materials and methods

2.1. Material

In order to demonstrate the methods, human mandible samples were used. The samples were scanned by 64-slice CT (MSCT) (Aquillion 64, Toshiba, Japan), with resolution of 512 × 512 px, and slice thickness of 0.5 mm. Same samples were used as the one presented in Ref. [12]. The Software used for the development and implementation of the methods is Dassault Systems® CATIA V5 R21.

2.2. Methods

The novel methods presented in this paper are based on the unit cell approach, but with the implementation of two important improvements.

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The first and most important improvement is the application of MAF for the definition and creation of the scaffold 3D model. Therefore, a short introduction of MAF is required. MAF is the result of our previous research, and it has already been applied for the creation of personalized 3D models of bone or bone parts for various human bones, including mandible [12], femur and tibia [10,11]. MAF can be applied to every human bone, and as a result of the method application, a parametric geometrical model of specific bone can be created. A parametric model is defined by a set of parametric functions, which represent coordinates of specific points on generic bone surface. Each point coordinate (X, Y and Z) is defined by an individual parametric function. Parametric functions are developed by the application of statistical or artificial intelligence methods on the set of bone samples [12]. In order to personalize a model to the specific patient (specific bone), morphometric parameters are acquired from medical images (e.g., X-ray, CT) for that patient, and applied in parametric functions. The presented procedures define basic MAF. Extended MAF contains various techniques which can be applied on a personalized bone model, and in that way, expand possible applications of the method, e.g. for the creation of implants models [13,14]. The application of MAF for the creation of scaffold 3D models brings two important benefits to the design technique:

- Creation of the CAD model of the missing part of bone is automatically created by the application of MAF.
- Scaffold model inner architecture is semi-automatically created by the application of MAF.

The second important modification is the application of parametrically defined nucleus elements. A nucleus is a straight or curved bar limited by two nodes (Fig. 1a), and it represents a basic building block for scaffold modelling. Nucleuses can be created with the application of different shape and size of cross-sections, and with different lengths, as presented in Fig. 1b.

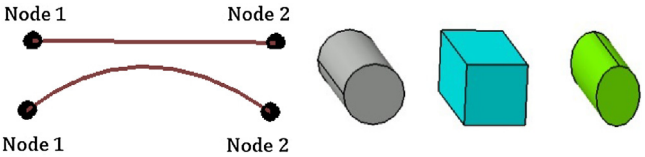

Fig. 1. Shapes and cross-sections of nucleus elements.

The nucleus cross-section and length dimensions, applied in presented examples, are arbitrary. For each individual patient, they should be personalized.

The first developed method is a Curve Based Method (CBM), and second is a Pattern Based Method (PBM), as presented in Fig. 2. As a result of the application of both methods, scaffold 3D models are created. Both models are based on the nucleus elements, but the difference is in a manner of model construction.

For the CBM model, the defined nucleus parametric model is used as a basic construction element for the definition of scaffold architecture, as presented in Fig. 2.

For the PBM model, the nucleus element was used as a basic component for the construction of the unit cell, which was defined as 3D cross (Figs. 2 and 6).

The use of both methods involves performing three groups of processes: preparation process, shared processes, and method specific processes, as presented in Fig. 3.

The preparation process is a process which is performed in advance, and it enables the definition of the initial structure of scaffold components. Both methods include the process of nucleus length and cross section definition. To properly define a nucleus model as a parametric model, three entities were introduced: cross-section shape, cross-section dimension(s), and nucleus length.

As presented in Fig. 1, for each entity, one or more parameters were defined, or more specifically: the parameter cross-section

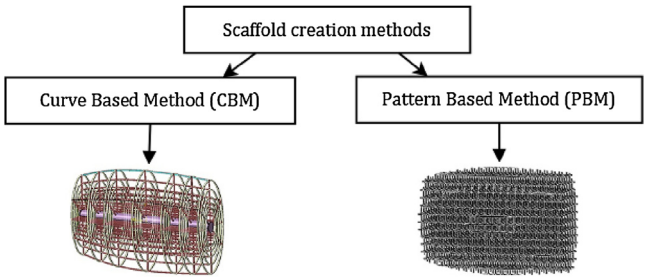

Fig. 2. Scaffold design methods.

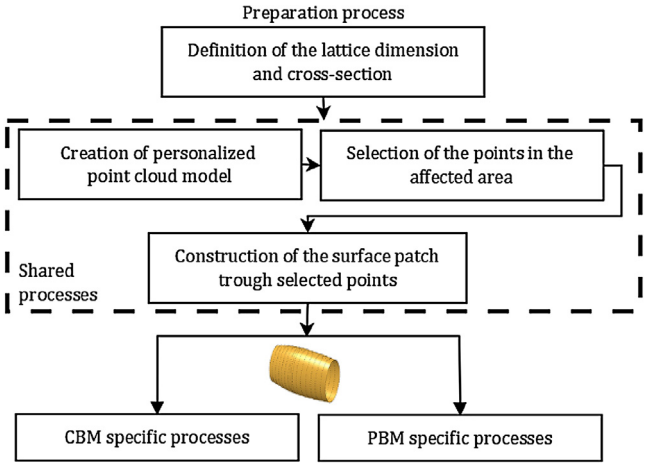

Fig. 3. Preparation, shared and specific processes for presented methods.

shape; the cross-section dimension defined for adequate shape (e.g. radius for circle); the nucleus length.

To conclude, the nucleus parametric model is defined as the function of three entities, as described in Eq. (1).

$$parametric\_nucleus\_model = f(cross\text{-}section\_shape,\ cross\text{-}section\ dimensions,\ nucleus\ length) \quad (1)$$

Shared processes are very important because they enable creation of the boundary surface of the missing part of the bone.

Among three shared processes, only selection of points in affected area requires involvement of surgeons because only they may decide where boundaries of resection are. Two other shared processes are done automatically in CATIA as shown in Refs. [10–12].

2.3. Curve Based Method (CBM)

This approach uses interpolated splines as guiding curves for grid construction. The first step is the definition of boundary radial splines, which are created as intersections between planes and the boundary surface of the missing part of the bone. The position of the planes mainly depends of the bone type [12]. The planes are created in respect to Referential Geometrical Entities (RGEs) [10–12], which are the essential part of MAF, and they are defined as geometrical entities (lines, axes, planes, etc.) which represent basis for the creation of bone geometrical models. Basic anatomical entities of the mandible are presented in Fig. 4a.

The next step is to construct scaled curves, as presented in Fig. 4b. Scaling and the following steps are done by the use of script created by authors and defined in VBScript in CATIA. In this step the scale factor is calculated according to the minimal defined nucleus length in radial direction. In this case, the minimal nucleus length is set to 5 mm, so the maximal calculated scale factor for the presented case is 0.6–0.8. The scale factor is calculated by using the gravity centre point for each curve and points on curves, for each model.

Homogeneous coordinates were used for the definition of points and for the scale calculations, as presented in Eq. (2). Curves are planar, so scaling is done in plane, and only two coordinates are

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