The Reverse Engineering of Human Organs Based on the Application of Method of Anatomical Features

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Abstract. The human body is often affected by some pathological processes or illnesses. In many cases, it is necessary to perform surgical intervention, sometimes in a very short period. Computer-Assisted Surgery - CAS defines a set of techniques that use computers and other devices for planning, guiding, and performing surgical interventions, and can greatly improve outcome of pre/intra/post-operative procedures. In this paper, the enhancement of the Method of Anatomical Features – MAF, which is defined as an essential part of CAS, is described. The MAF is improved by adding Characteristic Product Feature - CPF method as one of its essential processes, to better describe human organs and to create Feature models as their virtual representation. The created Feature models will greatly help physicians to better prepare and conduct surgical interventions, thus improving patient treatment and recovery processes.

Keywords: MAF, CPF, human organ, geometrical model.

1 Introduction

The human body is often affected by some pathological processes or illness. In many cases, it is necessary to perform surgical intervention, sometimes in a very short period. For the success of surgical intervention, it is particularly important to prepare a good pre-operative plan and to ensure that adequate implants are provided. Computer-Assisted Surgery (CAS) [1] defines a set of techniques that use computers and other devices for planning, guiding, and performing surgical interventions. The most important component of CAS is an accurate personalized model of the affected human organ (e.g., tendon, ligament, or bone). In general, such model(s) can be acquired by the application of two different approaches [2].

The first approach implies application of medical imaging technologies, like Computed Tomography (CT) or X-Ray, to provide 3D geometrical models of human organs. Such models can be created in three general ways:

- Application of software, which is part of a medical scanner (e.g. Vitrea)
- Post-processing of medical images in medical-oriented CAD programs (e.g. Materialise Mimics, 3D Slicer)
- Post-processing in one of the CAD software packages (e.g., CATIA, 3D Fusion).

One of the main drawbacks of this approach is the inability to create a geometrical accurate model of whole organ in cases where the scanned bone incomplete due to illness (osteoporosis, arthritis, cancer, etc.) or trauma (multiple fractures, crushed bones, torn ligaments and tendons, etc.), or when medical images are not of adequate quality. Examples of methods used in this approach are given in the works [3, 4].

The second approach for creation of 3D geometrical models of human organs is based on predictive geometrical or statistical model and data obtained from medical images. In predictive models, geometric entities are described by mathematical functions, whose arguments are morphometric parameters that can be read from medical images. With this approach it is possible to create an accurate 3D geometrical model of a patient's organ. [4, 5].

Method of anatomical features (MAF) is a methodology which can be used in both approaches [4]. In this paper, the research focuses on improving MAF by adding the Characteristics Product Features (CPF) [6] method. CPF enables the definition of different product features and properties, and thus it should provide MAF capability to define 3D models of other organs, not just bones. The initial approach to MAF enhancement is described in this paper for the definition of the Anterior Crucial Ligament geometrical model, which is based not just on anatomical and morphological properties but also on its functional characteristics.

2 Characteristic Product Features Methodology

The methodology consists of several steps defined as processes [6], and they are: Point Cloud Import (P1), Feature Description (P2), Feature Definition (P3), Feature Extraction and Implementation (P4). The process starts with importing point cloud and finishes with complete definition of selected product features, and their implementation. Point cloud is initially a set of points acquired from the scanning activity, where each point represents a minimal geometric definition of the scanned product. In the next process (P2) each product feature of interest is described semantically, and a list of features is created. This list can be represented using a plain text file or some other type of representation like a visual (sketch). Finally, it is necessary to conduct process P3 to provide a complete definition of feature(s) properties. This process is the most important activity in methodology application. It consists of several feature definitions and is not limited to those presented in [6] (geometrical, mathematical, functional, etc.). To define product feature(s) geometrically, it is required to use a filtered point cloud. Then, each product feature is defined by selecting a group of points that belongs to that product feature, i.e., product feature(s) is geometrically represented by a set of points in the point cloud.

The group of points can be further processed in remodeling steps, like creating mesh(es), forming geometrical elements like curves, and forming 3D models (surface or solid) at the end. Each following individual step can produce output and further define product feature(s). For example, the mesh element can be exported to an STL file and then joined to the point cloud file of the product, thus creating a set of files for an individual feature – point cloud (*.txt) and mesh file (*.stl). The whole set of product features of interest can contain many files for each component; if required, they can be used individually or assembled into the whole product and used as a part model, i.e., Feature(s) model. The one important capability of a product feature is the parametrization of its point set, thus creating a parametric point cloud model for a unique feature with the capability to adapt to different parameters, not just geometrical, but also to functional, technological, and so on. The CPF application is demonstrated in [6] for the creation of the ski shoe heel lip 3D printed model which was successfully implemented and used. In [6] the functional, geometrical, topological, and material features were defined, and they influenced the creation of heel lip geometrical and physical model by 3D printing.

3 Method of Anatomical Features

MAF [4] introduces a new approach to describe geometrical entities of human bones, and it enables creation of various geometrical models of the human bones and other organs. Two different types of models can be created by the original MAF:

- 3D geometrical models – These models are standard polygonal, surface and volume models which are used in CAD for many years. They are created by the application of standard CAD technical features in CAD software packages.
- Predictive (parametric) models of the human bones. By the application of the morphometric parameters acquired from medical imaging methods, these models can be adjusted to the geometry and morphology of the human bone of a specific patient.

Both types of models are created on the basis of data (input models) acquired from medical imaging methods (e.g. CT or MRI). MAF is a complex method, composed of basic and additional processes (Fig. 1), and therefore, Structured Analysis and Design Technique (SADT) [7] is used for its description. The main components of SADT diagrams are input elements, recourses, control elements, and output elements, defined in [4] and presented in Fig. 1.

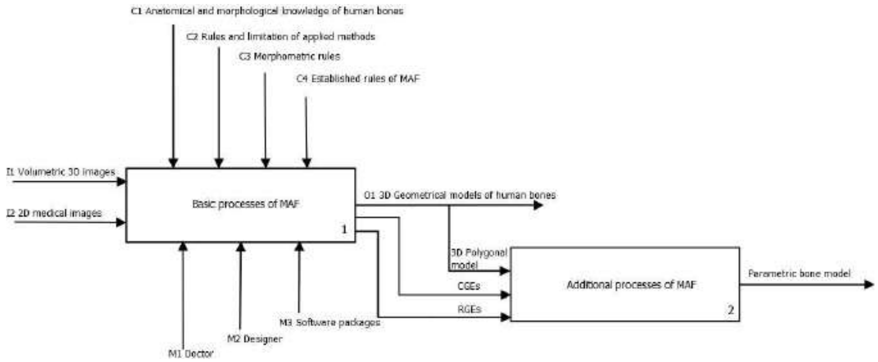


Fig. 1. Basic and additional processes of MAF [4]

Basic processes are defined in [4] and they enable complete geometrical and anatomical definition of the specific human bone. These processes are: Creation of initial polygonal model (A11). The output from this process is a polygonal model of the specific human bone; Anatomical analysis (A12). The outcome of this process is an anatomical model of the specific human bone; Definition of Referential Geometrical Entities (RGEs) (A13). These entities represent basic geometry which is used for the creation of all other geometrical elements like curves or surfaces; Creation of Constitutive Geometrical Entities (CGEs) (A14) – 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. Polygonal model, RGEs and CGES are outputs from the basic MAF processes. By the application of these outputs different geometrical models of the human bone can be created.

The output from MAF additional processes is parametric model of the specific human bone [4]. Parametric model is a predictive model which shape, and anatomy are defined by the formed parametric functions, and conditioned by the values of the morphometric parameters acquired from medical imaging methods. Parametric model can be transformed into the personalized model by applying unique values of morphometric parameters acquired from specific patient's medical images.

The MAF is a proven method, and its results are well known [8 - 12]. The original MAF was developed to create geometrical models of human bones [2, 4, 8-11]. The results presented in these studies demonstrated the geometrical accuracy and anatomical and morphological correctness of MAF application. It is essential to mention that the quality of the models created by MAF can be defined and influenced by the requirement of a clinical case, like the one presented in [9] where a sternum implant was created using initial MAF procedures and additive technologies. The implant was successfully implemented into the patient, and the patient recovered. Additional examples of MAF application are defined in chapters [10 - 12] in the Springer book “Personalized orthopedics”. Besides bones, MAF is also used to create personalized implants for human bones (long and flat) as presented in [8, 11, 12]. The one characteristic application was creating a plastic mandibular reconstructive plate model, for the young male patient with progenia, presented in Fig. 2.

Fig 2 a) X-ray scan with basic geometry b) Solid model of the personalized plate created over scanned data by using MAF c) printed models of the plate implants (left and right) [8, 11]

The plastic model (Fig. 2c), manufactured by FFF 3D printing, was used to guide real plate bending in the preoperative phase. The bent model was geometrically accurate and fitted the patient perfectly. Also, it is important to note that the presented approach shortened the surgery time, which is always a good thing for a patient. To conclude, MAF can be used to create geometrical models of human bones and implants, and concerning previous applications, results are more than satisfactory. For now, the authors have not found a case in which MAF cannot be applied, because it allows different capabilities to bone remodeling as presented in [4]. Concerning ethical principles, MAF is oriented to digital (geometrical models), and for every real (clinical) application presented in the references and other MAF applications, ethical regulations were and will be followed.

The focus of this research is to enhance MAF, and for that, it is necessary to create specific modifications. The first modification, presented in this study, is an application of the CPF method as one of the basic processes in the methodology definition. The upgraded MAF basic processes with CPF are presented in Fig 3. CPF method enables various definitions of any product feature with a specific output. As already stated, any product or organ feature can be extracted from the point cloud or polygonal model, and existing or required properties can be defined. In MAF the original procedure is to acquire cloud point from medical imaging methods, then conduct geometrical filtering and transformations and produce some geometry (RGEs, CGEs, and other geometrical entities and models).

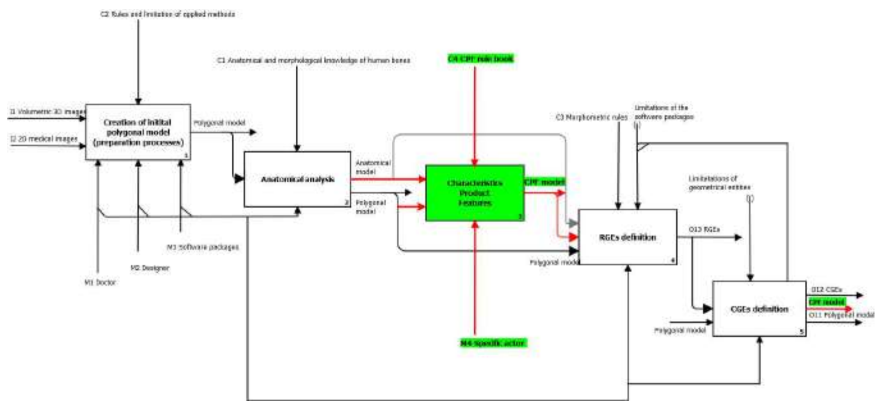


Fig. 3 The addition of CPF to MAF basic processes

CPF (Fig.4), adds more capability to MAF to define specific features on the human organ and to add more characteristics, not just anatomical ones. Therefore, the resulting model can have additional properties, like required functional or mechanical characteristics. It is important to note that the term model in this context refers to a complex entity composed of different elements (CGE, polygonal model(s), CPF properties), and it will be referred to as Features Model (FM) (specific CPF model). To make a conclusive statement: The resulting FM of the MAF application can reflect various needs and fulfil different requirements from different actors. FM can be used as input model to additional MAF processes to enable better parameterization according to the novel specifications defined in FM.

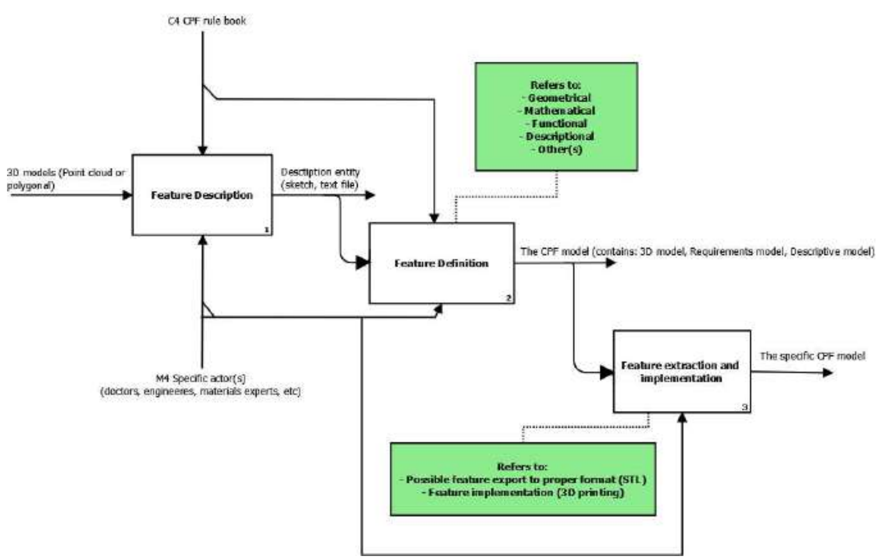


Fig. 4 The CPF basic processes

4 Method application for Anterior Crucial Ligament remodeling

In this research, the Anterior Crucial Ligament (ACL) is used as an example for the remodeling of the knee ligament based on different requirements defined in CPF model. Three bones meet to form the knee joint: the femur (thighbone), tibia (shinbone), and patella (kneecap). The kneecap sits in front of the joint to provide some protection. There are four primary ligaments in the knee, and they act like strong ropes to hold the bones together and keep the knee stable. The ligaments connecting the knee bones are: Collateral Ligaments - These are found on the sides of knee; The medial collateral ligament (MCL) is on the inside, and the lateral collateral ligament (LCL) is on the outside. The detailed explanation of ligaments can be found in [13]. One of the most common knee injuries is an ACL sprain, or tear. The main technique for ACL repair is to use tendon graft(s) and to fixate it with screws positioned in the femur and tibia. It is approach used for many years with different results. The other novel approach presented in [14, 15] demonstrates categorically that there is a place for ACL repair with InternalBrace (Fig. 5). Early repair of new joints has an impact on protecting joint health and restoring normal biomechanical function. An ACL repair augmented with the InternalBrace procedure protects the cartilage, reducing the need for resection. Standard repairs with ACL Reconstruction Hamstring Tendon are most prone to resection and arthritis. This approach in ACL reconstruction is due to the concerns regarding the high level of arthritis associated with traditional reconstruction, (reported to be as high as 48% after 10 years).

With InternalBrace, over 80% of the repair patients did not need any form of reconstructive surgery on their knees during the 5 years of follow-up. Those that did still made a tremendous recovery after a second-stage revision procedure using a reduced graft – again supported with the InternalBrace. The difference between the standard and novel approach is that ACL repair with InternalBrace is a lot less traumatic for the joint, as presented in Fig. 6. Repair augmented with the InternalBrace only requires small bone tunnels which take the 2mm InternalBrace. Compared this to the major bone tunnels that need to be drilled during a traditional reconstruction (2.4 mm for femur and 3.5 mm for tibia). There is far less bone trauma in an ACL repair augmented with the InternalBrace, compared to a traditional reconstruction.

Fig. 5 The ACL InternalBrace reconstruction [15]

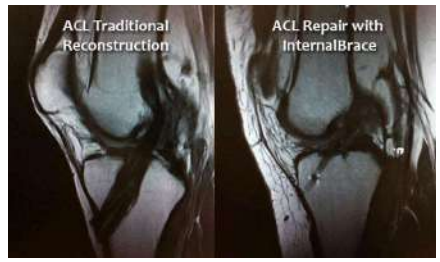


Fig. 6 Comparison of traditional and InternalBrace reconstruction [15]

To create a 3D personalized model of the ACL it is required to define important functional characteristics of the selected treatment case. Because of the novelty of the research and good prognosis, a second case is selected – InternalBrace. The complication of ACL reconstruction may be summarized as the ones due to pre-operative decisions, intraoperative causes, and postoperative causes. The focus of this study will be on pre-operative and post-operative complications which can be reduced with good preoperative analysis of the injured knee, and some of them can be:

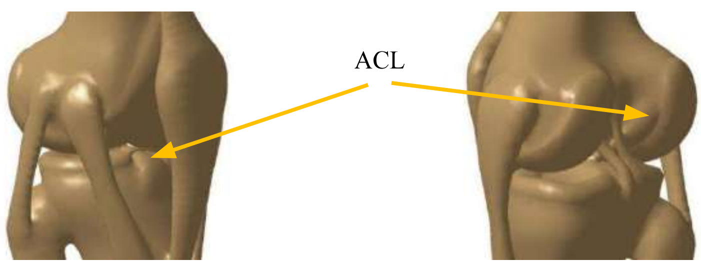
- Preoperative assumptions and decisions
  - ACL reconstruction is deferred until the swelling has subsided after an acute injury.
  - Not performing the ACL surgery when needed and waiting for too long may lead to damage to the articular knee cartilage and meniscus.
- Postoperative complications
  - Stiffness is a common post-ACL reconstruction complication that is defined as the incomplete range of motion of the knee following surgery.
  - Patella fracture after ACL reconstruction may result from graft harvesting (only in resection for this case).
  - Pain, swelling, redness, the rise of temperature, and stiffness may occur because of infection.
  - Pain in the front of the knee after the surgery is commonly associated with patellar tendon graft but may also occur in cases of allograft and quadriceps tendon graft.

The stated complications are entry point for the CPG/FM model creation, and they represent the functional and geometrical requirements, which 3D ACL model needs to fulfill. The fulfillment of these requirements will allow better definition, creation, and application of the ACL implant. The personalized 3D model created in the pre-operative procedures with accurate geometry, and with complete positional definition of femur and tibia holes and InternalBrace dimension, will help physician to properly implant the InternalBrace, eliminating the need for tendon graph and thus, reducing potential risks, like patella fracture and infection. Summarized geometrical requirements based on the defined complications for the clinical case are defined as:

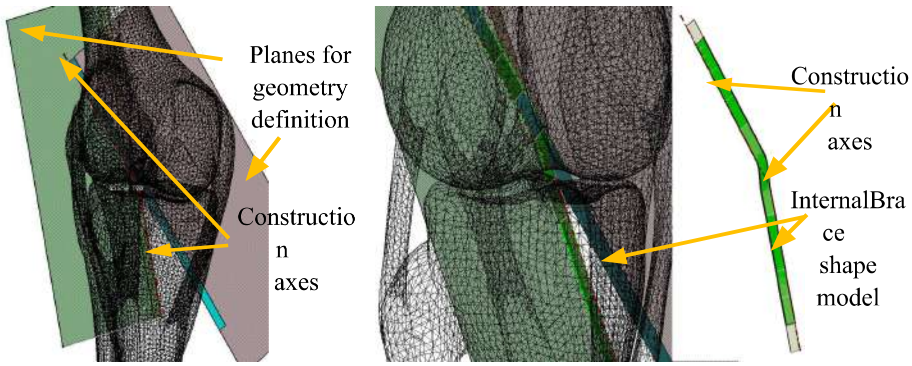
- Accurate geometry of femur and tibia. Anatomical axis aligned in Anterior-Posterior (AP) plane.
- Simplified geometrical model of the ACL – Positional accuracy is required.
- Sheet model (3D model with small thickness) of the bracelet.
- Parametrical model of the bracelet (will be completely defined in future research).

The MAF method already provides methods and procedures for the creation of the acurate personalized geometrical models of the femur and tibia (and other long and flate bones) [2, 4]. These models can be used as the basis for the creation of the ACL simplified model. As the example of the model creation in the Fig. 7, different 3D models are presented. In the Fig. 7a 3D presentation model of the knee is shown (originated from CT scan, Clinical Center Nis, Serbia, reolution: 512x512,0.5 mm slice thickness), and in the Fig.7b 3D model of the knee and the braclet is displayed. The models are prepared in CATIA (licensed), but they can be exported to the independet formats like STEP, or IGES and used freely. These models can help surgeons propely prepare surgical interventions using CAS with CAD software and prevent some of the stated complications.

The FM created for the InternalBrace includes geometrical, functional, and material models. The braclet geometrical model is defined by using already defined geometrical models of tibia and femur. Two axes are constructed to define InternalBrace direction through femur and tibia. The width and length of the InternalBrace are parametric values, which mean it can be defined as a feature parameter, and changed accordingly. The functional requirements are stated in the previous section, while material is defined according to the clinical application (FiberTape® suture - polyethylene). By creating this kind of FM, the different modifications are available to the designers and surgeons to prepare and conduct surgical interventions.



a) The 3D model of the knee with ACL ligament



b) The knee and InterBrace 3D model with defined geometry

Fig. 7 The InterBrace and knee 3D model created by using the enchanced MAF

5 Conclusion

The human model reconstruction process is a complex one. Therefore, different methods for its creation are presented in this paper. One of these methods is the Method of Anatomical Features (MAF) created by the authors of this research, which focuses on the design of 3D models of human bones and implants. Furthermore, this study demonstrates the enhancement of MAF by adding the Characteristic Product Features (CPF) method as a MAF process. Using this approach, it is possible to create different types of complex models (functional, geometric, material) of human organs and apply them in Computer Assisted surgery (CAS), thus improving patient treatment and recovery processes.

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