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Original Research Article

Predictive geometrical model of the upper extremity of human fibula

Milica Tufegdzic [a,*], *Stojanka Arsic* [b], *Miroslav Trajanovic* [c]

[a] *Department for Mechanical Engineering, Machine-electrotechnical School, Krusevac, Serbia*
[b] *Department of Anatomy, Faculty of Medicine Nis, University of Nis, Nis, Serbia*
[c] *Department for Production, IT and Management, Faculty of Mechanical Engineering, University of Nis, Nis, Serbia*

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ABSTRACT

Computer assisted preoperative planning in orthopedic surgery, as well as designing and manufacturing of personalized fixators, implants and scaffolds requires a good three-dimensional model of bone(s) of the treated patients. Existing methods that convert the Computer Tomography (CT) images into the polygonal three-dimensional models are time-consuming and inefficient. Therefore, we propose a predictive model that allows quick creation of three-dimensional (3D) surface model of a particular bone by measuring the relevant parameters from an X-ray or CT image.

In this paper, we present the process of creating a predictive geometrical model using the case of proximal end of fibula as an example. The predictive model is built by defining the referential geometric entities that correspond to anatomical features, based on which appropriate points, axes, planes and curves are created. Using the method of linear and nonlinear regression with four different parameters, which can be measured from X-ray images or anterior-posterior projection of fibula at CT scans, the equations for X, Y and Z coordinates of the selected 168 points are obtained and their predictive values are calculated. These values are used for creating 3D surface model with the aim of two different methods: using loft function and converting these coordinates into point cloud. These models were compared and verified through analysis of deviations and distances between initial model and predictive models. The resulting 3D model has satisfactory accuracy, and the process of its building is much shorter.

* *Corresponding author at*: Department for Mechanical Engineering, Machine-electrotechnical School, Cirila i Metodija 26, 37000 Krusevac, Serbia.

E-mail addresses: miltufegdzic@gmail.com (M. Tufegdzic), stojanka@medfak.ni.ac.rs (S. Arsic), miroslav.trajanovic@masfak.ni.ac.rs (M. Trajanovic).

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1. Introduction

Three-dimensional (3D) models with accurate geometric representation of the long bones are being increasingly used for various aspects of clinical practice and research. They are an indispensable basis for preoperative planning in orthopedic surgery, designing and manufacturing of personalized fixators, implants and scaffolds.

There are many programs that allow obtaining the polygonal 3D models of bones based on Computer Tomography (CT) images in DICOM format. Independently from the program, building a 3D surface model of a bone from CT scans must be conducted through several steps: data management, image enhancement, segmentation and 3D reconstruction [1]. Defining the boundaries of the bone is necessary for healing of the model, but it often cannot be done accurately, the process is time consuming and requires a great deal of patience. It is well known that in clinical practice the patient cannot undergo a CT scan because of previous exposure to very high levels of ionizing radiation. In such cases it is impossible to build a 3D model of a bone. Our idea is to create a method for obtaining a predictive model of long bones from X-ray or CT images, using Computer Aided Design (CAD) program and statistical tools. In this paper, we are presenting the method using the upper extremity of human fibula as an example.

According to the anatomical description, the human fibula is a long, slender bone, located at the lateral aspect of the leg. It has three main parts: a proximal head, a narrow neck, a long shaft and a distal lateral malleolus [2]. The upper extremity of the fibula is composed of two parts, head and neck. The head of the fibula has a most prominent part called the apex and a flattened articular surface, which forms the proximal tibiofibular joint with a corresponding fibular articular surface on the lateral condyle of the tibia. Articular capsule is reinforced by the anterior and posterior tibio-fibular ligament of the fibular head. Main parts of human fibula are presented in Fig. 1 (down below).

It is important to point out, as an additional biomechanical and functional description of the fibular upper end, that there are two types of superior tibio-fibular joints, horizontal and oblique, due to the anatomical variations [3]. They provide a compensatory motion in internal and external rotational movements of the tibia. The primary functions of the superior tibio-fibular joint are: (1) the dissipation of torsional stresses which occur at the ankle joint, (2) wasting of the lateral tibial flexing, and (3) tensile weight bearing [3].

The previous work on the 3D modeling of the fibula or the parts of the fibula has resulted in generating a 3D model of fibula bone ankle joint (including the lower end of the fibula) by using software for processing the medical images and the CAD software. The process of the 3D modeling of human fibula using medical image software is described in [4]. IGES surface of the human fibula using MIMICS software and a 3D surface model in Solid Works, in order to test a newly developed and adapted osteosynthesis implant, used for transsindesmotic fibula's fracture is obtained in [5]. In another paper a finite element model of the knee joint, including distal femur, tibia, fibula, menisci, articular cartilages and ligaments is obtained from MR images of a healthy male [6]. The models of different bones such as distal femur, patella and upper extremities of fibula and tibia are obtained from the CT data. These CT slices were converted into the point clouds (using Mimics) and a CAD surface model was obtained in Geomagic. These CAD models were further processed for the purpose of Finite Element Analysis [7]. In order to study the influence of the fibula and talus on the distribution of stress on the tibia, a 3D solid model of the fibula was created using CT images for generating 3D solid models of tibia, fibula and talus, with the help of Mimics in the form of point clouds [8]. These point clouds were exported in Geomagic where the failure fixing and smoothing on the surfaces was performed. The 3D models were saved in STL format and later assembled using Mimics FEA module. A case of reconstruction of a maxillary defect and orbital floor with a micro vascular fibula graft is shown in [9]. An individualized titanium mesh, as a rapidly prototyped template for the missing part of fibula, is designed from a CT scan using Materialize.

3D surface model of the fibula was obtained in the process of Reverse Engineering (RE) [10], but this process was time-consuming, as all processes mentioned above.

2. Materials and methods

In the process of generating a predictive model of the proximal end of human fibula, a method of anatomical features (MAF) was used. This method was previously described in [11] and has been implemented on femur and tibia bones. In the case of fibula bone, first few steps of this method were applied in our research. But, because of the fact that linear regression was not suitable for fibula bone, the method was expanded by introducing different nonlinear regression models. These models were tested by statistical tools and for the level of significance a value less then 0.05 was adopted. In order to determine the most suitable model, from those which were statically significance, we have chosen one bone from the sample for which the value of the length of mechanical axis is the closest to the mean value of the sample. Regression values of coordinates for corresponding points on this bone were calculated for each model and compared with initial values. So, for the models were adopted the ones for which the difference from regression values was the least. Finally, we have created predictive geometrical models from the regression coordinates, with the aim to compare and verify our results using the deviation and distance analysis.

So, our research was conducted through the following steps:

- CT scanning and digitalization of data,
- definition and determination of anatomical landmarks on the upper and lower end of fibula,
- creation of the referential geometric entities (RGEs) (points, axes, planes, surfaces) according to the anatomical and morphological characteristics of the bone [12,13],
- selection and measurement of the parameters on the upper end of the fibula,
- identifying and measuring the coordinates of the points for which the regression models are formed,
- mathematical models determination of the regression equations,