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TOWARDS DIGITAL TEMPLATE FOR ARTIFICIAL HIP IMPLANTS SELECTION

Goran DEVEDŽIĆ[1], Suzana PETROVIĆ[1], Saša ĆUKOVIĆ[1], Branko RISTIĆ[2,3], Zoran JOVANOVIĆ[3], Miloš ĆIROVIĆ[1]
[1]Faculty of Mechanical Engineering, Sestre Janjić 6, Kragujevac, Serbia
[2]Faculty of Medicine, Svetozara Markovića 69, Kragujevac, Serbia
[3]Clinical Centre Kragujevac, Clinic for Orthopedics and Traumatology, Zmaj Jovina 30, Kragujevac, Serbia
devedzic@kg.ac.rs, suzana.petrovic@mfkg.rs, cukovic@kg.ac.rs, branko.ristic@gmail.com, zjovanovic@medf.kg.ac.rs, cirovic.milos@gmail.com

Abstract: *Technology of so-called "digital templating" is based on 3D parametric models of femur and endoprosthesis of hip. It is aimed in pre-operative planning, primarily for artificial hip implants selection, as well as visualization tool for other surgical activities planning. Parametric master model of a femur is developed from a series of 2D and 3D images obtained by different scanning methods, which include both X-ray based and optical. In that course, for the initial model we use optically scanned 3D images of cadaveric bones and their educational replica. Generated clouds of points are optimized during reconstruction process to ensure proper polygonization and creation of surface and solid models. Parametric definition of a femur uses a set of cross-sectional parameters that provide anatomically consistent individualization (customization) of the master model. Family tables for different designs of endoprosthesis are also developed. The process of artificial hip implants selection assumes automatic positioning of a stem into femoral channel during which developed control mechanism calculates both the overlapping volume and the clearance between cortical bone and the stem. Depending on individual characteristics of a patient and orthopedic surgeon preferences the system ranks the alternatives and visualizes the correspondent data and solutions.*

Key words: *Free-form modeling, reverse engineering, femur, endoprosthesis*

1. INTRODUCTION

Planning of the surgery and the choice of type and size of the implant is a very important part of preoperative preparation of patients prior to installation hip arthroplasty. Total hip replacement (THR) is one of the most applied surgical operations today, aiming in elimination of pain and restoring gait capabilities. In a total hip replacement, both acetabular and femoral head are replacing by metal and plastic parts [1]. Traditionally, orthopedic surgeon uses transparent foils of the stem and acetabular cup together with X-ray film for selection of proper implant type and sizes [1], [3]. Extensive development of the computer assisted surgery (CAS) techniques brings new abilities and much more precise procedures [4], [7-9]. We present new approach to so-called *digital templating* of the THR preoperative planning, based on 3D parametric model of the proximal femur and hip endoprosthesis.

2. PARAMETRIZATION OF FEMUR AND PROSTHETIC IMPLANTS

2.1. Femur reconstruction

The approach to the reconstruction of the scanned object's surfaces depends on their geometrical regularity, i.e. whether these have proper shapes or represent free-form (sculptured) shapes. The algorithm of sculptured surface reconstruction is shown in Fig. 1. and consists of three complementing phases: the points phase, the polygon phase, and the surface phase.

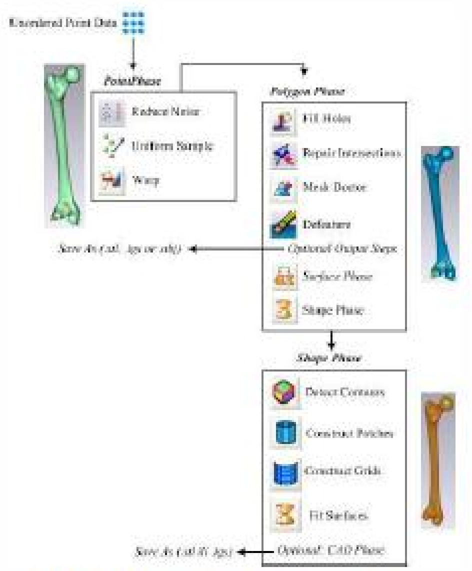


Fig.1. *The algorithm of sculptured surfaces reconstruction*

During scanning process a measurement system generates cloud of points that represents the shape of the scanned object. We used ATOS IIe optical measurement system. Points phase usually involves optimization and reduction of the number of discrete shape samples in order to simplify the representation of an object for further application, keeping its consistency and meaningfulness [2], [6].

Conversion of optimized cloud of points generates polygonal model of the shape. This phase ensures the detection, removal, repair and relaxation of the set of polygons (triangles) and determines the level of smoothness of the polygonal surface through noise reduction.

The surface phase results in the creation of NURBS-based surface model using the smoothed grid of the polygonal model. After the refinement, surface model is ready for further application, which includes solid modeling, analysis, etc. [4-5], [7-8].

2.2. Definition of femur axes

Parameterization of a femur is based on determination of characteristic cross sections and the set of sufficient number of the parameters that describe femur's shape in anatomically consistent way. We present the approach to femur axis determination that uses the set of the centers of gravity for the each characteristic femoral cross section (Fig.2). The femur axis consists of the two counterparts, namely shaft's axis and neck's axis, which are fitted to the set of characteristic points and smoothed.

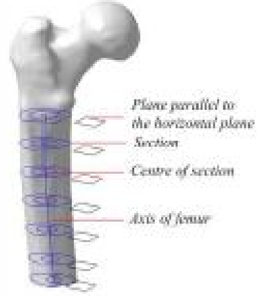


Fig.2. *Axis of a femur's shaft*

From the anatomical point of view, femoral head has spherical shape. Determination of the neck and head axis requires the point of the head's center, as well as the set of other spatial geometrical entities shown in the frontal (Fig.3) and horizontal planes (Fig.4).

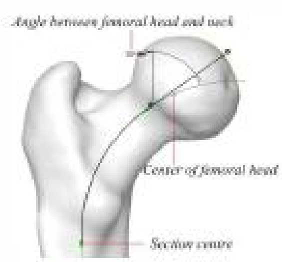


Fig.3. *Axis of a femur's neck in the frontal plane*

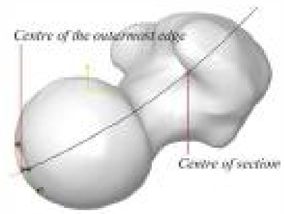


Fig.4. *Axis of a femur's neck in the horizontal plane*

2.3. Parameterization of the femur

The femoral axis is the support for the cutting planes that generate cross sectional profiles. The cutting planes are normal to the smoothed axis in the points of the aforementioned characteristic set (Fig.5).

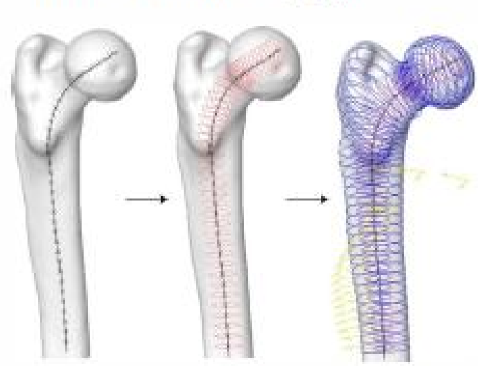
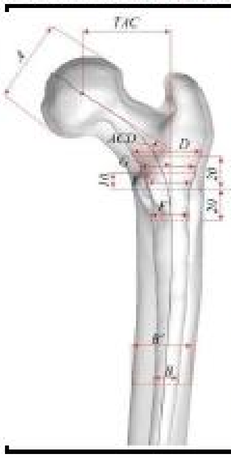


Fig.5. *Femoral cross sectional profiles*

In order to provide individualization (customization) of the master model the appropriate scaling is required. Analyzing the anatomical features given in the [3], [4], [5], [7] we have adopted the parameters, their values and ranges. Using the ranges and the extreme values in the characteristic femoral cross sections we have calculated scaling coefficients shown in the Table 1. To prevent violation of anatomical consistency during customized scaling we introduce the set of rules that have the role of control mechanism.

Table 1. *Scaling coefficients in the characteristic cross sections*



Region and scale factor
Neck shaft angle (ACD)
Offset (TAC)
Head diameter (A) *RA: from 0.79 to 1.50*
Metaphyseal width (D) *RD: from 0.71 to 1.56*
Metaphyseal width (G) *RG: from 0.59 to 1.41*
Metaphyseal width (E) *RE: from 0.76 to 1.79*
Metaphyseal width (F) *RF: from 0.78 to 1.83*
Intramedullary diameter (B) *RB: from 0.56 to 1.77*
Extramedullary diameter (B') *RB': from 0.82 to 1.47*

3D parametric-based geometry of a femur, which creates so-called master model capable to adapt to customized anatomic values of each individual patient, results from blending operation applied to cross sectional profiles along femural axis under rules of control mechanism. Figure 6 shows outer 3D geometries of femoral cortical (a) and trabecular (b) bone.

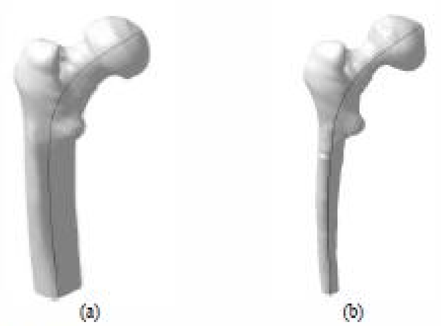


Fig.6. *3D geometry of cortical (a) and trabecular (b) bone*

2.4. Implants parameterization

The model of an implant is defined by the set of parameters, which directly affect the selection process [3-5], [7], [8]. The most influential are stem shaft diameter (A), length (B), neck length (D), and offset (C) (Fig.7). These parameters, together with other ones that completely describe implant design, define the family table, i.e. the set of implants' models available on the market, specific for a particular manufacturer, or the most frequently used in a certain clinic.

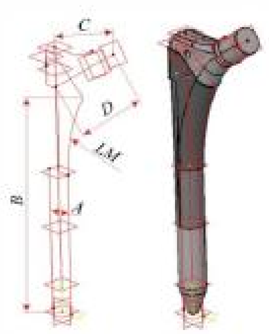


Fig.7. *Skeleton model of a stem*

The same procedure is aplied for other parts of artificial hip prosthesis.

3. DIGITAL TEMPLATE

The implant selection by comparing the radiological images and implant film, although the most frequently used, has its own deficiencies. One of the main drawbacks relates to the enlargement in radiographs, which may not necessarily be in proportion to the real case, causing mismatching during the operation. Development of 3D digital template aims in more precise and reliable pre-operational planning.

Prior the implantation of a stem medullary cavity is reamed in order to extract the marrow and properly shape the stem shaft intramedullary seat. Reamed medullary cavity has straight axis that matches implant's axis, while intremedullary canal matches spatial femoral axis. Hence, spatial axis of metaphysis should be approximated by a straight line, and additionally set user defined planes that define femoral anteversion angle required for proper implant insertion (Fig.8).

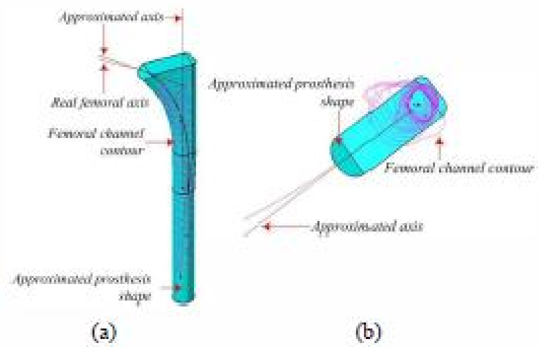


Fig.8. *Profile of intremedullary canal and the model of a reamer: a) isometric view, b) horizontal plane view*

Since the reamer has the regular shape, in the contrary to intremedullary canal that has irregular shape, one of the important criteria in reamer shape and size selection is to satisfy that the reamer profile tightly circumcircle the canal's contour edges (Fig.9). This criterion should be fulfilled at as many cross sections along femoral axis as possible. Control mechanism performs the optimization of the selection process.

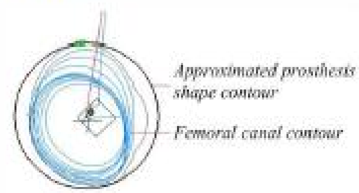


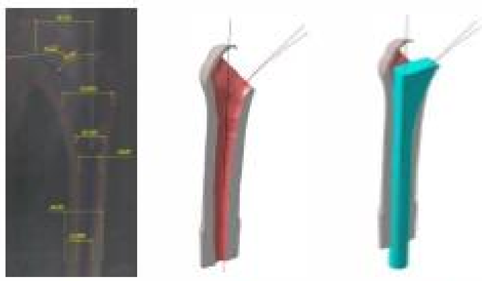
Fig.9. *Matching reamer size*

Customization of the generic model of a femur requires inputting parameters' values (Tbl.1) by measuring correspondent distances on radiographs (film or digital format) (Fig.10a). According to the rules of the control mechanism, the master model regenerates the master models of femur and implant (Fig.10b,c).

Selection process uses implants' family table to choose between available alternatives that suits current parameter

[1] Goran Devedžić, PhD, Faculty of Mechanical Engineering, Sestre Janjić 6, Kragujevac, Serbia, devedzic@kg.ac.rs
[2] Suzana Petrović, PhD student, Faculty of Mechanical Engineering, Sestre Janjić 6, Kragujevac, Serbia, suzana.petrovic@mfkg.rs
[3] Saša Ćuković, PhD student, Faculty of Mechanical Engineering, Sestre Janjić 6, Kragujevac, Serbia, cukovic@kg.ac.rs
[4] Branko Ristić, PhD, Faculty of Medicine, Svetozara Markovića 69, Kragujevac, Serbia, branko.ristic@gmail.com
[5] Zoran Jovanović, Clinical Centre Kragujevac, Clinic for Orthopedic and Traumatology, Kragujevac, Serbia, zjovanovic@medf.kg.ac.rs
[6] Miloš Ćirović, PhD student, Faculty of Mechanical Engineering, Sestre Janjić 6, Kragujevac, Serbia, cirovic.milos@gmail.com

values and surgeon preferences. In addition, rules of the control mechanism check for other constraints and anatomical/surgical consistency – for instance, an average clearance between walls of intremedullary canal and stem body should be within preferred value (Fig.11). By comparing the geometry of customized femur and intremedullary canal shape the built-in rules search for optimal size and shape of the implant. Finally, the control mechanism provides the alternatives ranking.

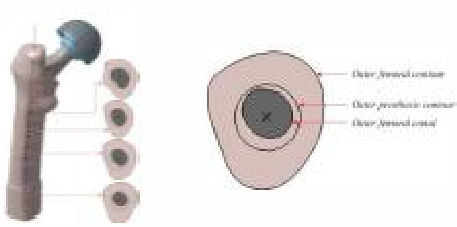


(a) (b) (c)

Fig.10. *Regeneration of the master models: a) radiograph of a proximal femur, b) master model of femur, c) matching master models of femur and implant*

Fig.11. *Checking the implant alternative*

Confirmation of the optimality of selected implant is performing by analysis of stem fitness in different cross sections along femoral axis, in horizontal and/or frontal plane (Fig.12).



(a) (b)

Fig.12. *Stem fitness in different cross sections*

Final stage of implant selection involves analysis of estimated bone mass that will be removed during reaming and medullary cavity preparation for stem insertion. Figure 13 shows an estimated bone mass of 9 grams, as well its distribution along the intremedullary canal.

Fig.13. *Estimated removed bone mass and its distribution*

4. CONCLUSION

Technology of so-called digital templating provides more precise preoperative planning of total hip arthroplasty. The methodology uses master (generic) parametric models of femur and implants that automatically regenerate upon entering customized anatomical values of the proximal femur parameters. Automated procedure for the analysis of shape and size of the prosthesis provides its optimal selection in each individual case. Furthermore, the analysis may yield to determination of an implants' ideal shape and size that supports the custom-based prosthesis manufacturing.

In addition, the whole methodology may be used in solving biomechanical problems (stress analysis, deformations), prosthesis production, and education.

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