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Editorial

3D reconstruction of bony elements of the knee joint and finite element analysis of total knee prosthesis obtained from the reconstructed model

ABSTRACT

Keywords:

Total knee prosthesis (TPK)
MRI segmentation
3D-CAD model
Polyethylene insert (PE insert)
Finite element analysis (FEA)

Two separate themes are presented in this paper.

Aims: The first theme is to present a graphical modeling approach of human anatomical structures namely, the femur and the tibia. The second theme involves making a finite element analysis of stresses, displacements and deformations in prosthetic implants (the femoral implant and the polyethylene insert).

Objectives: The graphical modeling approach comes in two parts. The first is the segmentation of MRI scanned images, retrieved in DICOM format for edge detection. In the second part, 3D-CAD models are generated from the results of the segmentation stage. The finite element analysis is done by first extracting the prosthetic implants from the reconstructed 3D-CAD model, then do a finite element analysis of these implants under objectively determined conditions such as; forces, allowed displacements, the materials composing implant, and the coefficient of friction.

Conclusion: The objective of this work is to implement an interface for exchanging data between 2D MRI images obtained from a medical diagnosis of a patient and the 3D-CAD model used in various applications, such as; the extraction of the implants, stress analysis at the knee joint and can serve as an aid to surgery, also predict the behavior of the prosthetic implants vis-a-vis the forces acting on the knee joints.

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1. Introduction

After it's development, about a half century ago, the first prosthetic knee joint replacements in the therapeutic arsenal against disabling arthropathy were performed. Through the use of medical imaging (X-ray, MRI, CT etc.), the adaptation of TKP and further research, an improved model has evolved which gave better reproducibility with respect to movements and stresses in the knee. The quality of the modeling process, in this case, lies in its ability to adjust to the shape of the knee joint and to preserve its geometry and topological integrity.

The first part of this study deals with the 3D reconstruction of bony elements of the knee joint. However, since the geometry and mechanical properties of the human knee joint are very complex, 3D-CAD modeling is a rudimentary yet

useful way to study the knee joint while allowing for a variety of applications, such as:

- Performing simulations for predicting the behavior of the bones in various situations;
- Extraction of prosthetic implants;
- Aid in diagnosis and surgical simulations.

The knee joint allows for a wide range of motion while supporting the weight of the major part of the body. Knowing the limitations and distribution of stress on the contact surfaces of the various parts of the implant are considered essential, reliable tools in predicting prosthetic applications, in particular the PE insert. This is a key element in predicting an implant's early failure and longevity. This will be addressed in the second part of this paper.

The diversity of topics in the field covers a wide range of the state-of-the-art.

Camacho et al (1997)¹ had developed an automated method to generate finite element meshes of geometrically complex structures from CT scans using solely hexahedral elements. This technique was an improvement over previous voxel-based mesh reconstruction by smoothing irregular boundaries at the model surfaces and material interfaces.

Janssoone et al (2009)² have developed an algorithm in C++ to generate a 3D volume of the knee using MRI imaging.

Villa et al (2004)³ studied the contact forces at the PE insert of the knee prosthesis with the mobile tray by using a finite element model and experimental tests.

Fregly et al (2005)⁴ used the dynamic method to determine the contact pressure during a gait cycle and calculated the areas and volume of polyethylene wear in the knee prosthesis fixed tray.

Knight et al (2007)⁵ developed a model of adaptive mesh of PE wear and compared this to a simulated experimental knee prosthesis.

In this paper two related aspects of work are described. In the first we propose a simple approach for 3D reconstruction of the bony elements by MRI imaging. This work is composed of three phases, the first step focuses on the acquisition of data from MRI images, the second is the segmentation step which discerns the edge definition of the image, and the third step is the 3D-CAD model which includes the generation of the model from the results of the segmentation.

The second part of this work describes a static finite element analysis of the PE insert and the femoral implant to determine the distribution of stresses, displacements, and deformations in these components during a normal gait cycle.

2. 3D reconstruction of the bony elements of the knee (femur and tibia)

2.1. Processing steps

The process can be summarized in three steps:

1. Data acquisition;
2. MRI segmentation;
3. 3D-CAD modeling.

The 3D-CAD model obtained can be used for extraction of the prosthetic implants, stress analysis, and for assistance in orthopedic surgery.

2.1.1. Data acquisition

As a first step, it is necessary to make a scan of the lower limbs (knee joint) of the subject in an MRI machine (Magnetic Resonance Imaging) to produce image sequences taken from 2D sections axially.

The MRI images on which we worked were in DICOM format (Digital Imaging in Medicine and Communications). This is the standard format used in medical imaging. It was introduced in 1985 to standardize data from different

instruments: X-ray, MRI, CT, etc. DICOM can store a lot of patient information such as material status, age, examination, etc (Fig. 1).

The images used are exported from DICOM format (2D sectional images axially spaced from 0.3 mm or 3 mm), those results are:

- Type JPEG
- Dimensions (512 × 512) pixels (400 × 400) mm²

In our study, the scanning was done for two patients:

Patient 1: 581 images from [0, 176] mm by 0.3 mm interval.

Patient 2: 237 images from [0, 180] mm by 0.6 mm interval.

To access them, the extracted images are named individually according to their axial distances.

2.1.2. Segmentation

Our approach focuses on a segmentation technique which defines the edge of the anatomical structures, specifically the knee joint by application of the appropriate algorithm. In fact the algorithm we employ in this study corrects discrepancies in our processed images.

A characteristic intensity is necessary to identify the bones of the right and the left knee in the scanned images. Once the bone is discerned, the edge detection is effected by means of the optimal filter Canny.⁶ Improvement in edge definition is achieved in the bone images by varying the threshold (s) in the range [0, 1]. The resulting image is a binary matrix in which the non-zero digits designate the edge points. Also, all the coordinates (x, y) positions of non-zero digits in the matrix are incorporated into a text file (*.txt), after having included the (z) coordinate showing the axial distance of the image. Finally, the result of the segmentation of all images of the same

Fig. 1 – MRI images (DICOM) from data acquisition on an axial view.

Fig. 2 – Samples of the processed images with different threshold values.

patient is a single file corresponding to an organized scatter. This is illustrated by the following algorithm:

Algorithm 1. Algorithm for image segmentation

Input:

- Image, xi, yi, xf, yf

Output:

- Visualization of the image's edge
- File (*.txt): coordinates of the edge's points

Beginning:

1. reading the image:
 - ('Image.jpg');
2. Frame of the area of interest
 - X between xi and xf, (X: pixel)
 - Y between yi and yf, (Y: pixel)
 - Result: Image size $X \times Y$
3. Edge detection
 - $s = \text{threshold}$;
 - Edge (Image, 'Canny', s);
 - Display of the image on screen
 - Replace 's' to get a better result
4. Statement
 - $p = []$: a matrix
5. Storage of edge pixels

```

for i = 1: image size (X)
  for j = 1: image size (Y)
    if the value of the pixel (i, j) > 0
      Store the positions i and j
    end
  end
end
end

```

6. Coordinates (x, y, z) of the pixels of the edge
 - Calculation of the dimensions of the image framed in mm
 - Evaluate the coordinates (x, y) edge pixels from their positions (i, j) in the identified matrix.
 - Involve the z coordinate (axial distance of the image) at each point (x, y) of the edge
 - Storing the coordinates (x, y, z) in a matrix
 7. Display results
 - Display the matrix in a file (*.txt)
- End

2.1.3. 3D-CAD modeling

The CAD modeling phase is performed in a semi-automatic way using the module (Scan to 3D) of the software (Solid Works). This part is done in two main steps explained below.

2.1.3.1. Construction of the mesh. The organization of the scatter shows a few artifacts. However, removing artifacts and spurious data is recommended. Further refinements are made by filling the holes of the constructed mesh, then smoothing of the surfaces and edges. To handle this problem a Delaunay 3D triangulation is applicable. Then, the algorithm develops a polygonal surface by selecting the appropriate triangles of the 3D triangulation from geometrical and topological considerations.⁷

The mesh smoothing involves optimizing polygons triangulations reducing the residual noise in the polygonal model and refining the mesh by adding triangles. As a result, a smoother surface is obtained.

2.1.3.2. Creating parametric curves and smoothing of the model. With the wizard curve of Solid Works, a system of

parallel curves is created from the polygonal model, and the number and the distance between the curves are adjusted manually. In the phase of the curves smoothing, the complexity of the forms of the mesh models (tibial and femoral), has imposed a division into three parts for the femur, and into two parts for the tibia. Each part is individually smoothed and additional smoothing is done during the assembly of those parts.

2.2. Results

Now we present some results obtained during the various stages of the proposed process.

2.2.1. Image segmentation (edge detection)

These figures (Fig. 2a–i) show some samples of the processed images with three different values of the threshold (s).

These figures presented, summarize all the cases encountered in the segmentation of images. The analysis of these results leads us to conclude that the adequacy of the image edge detected is dependent, firstly, on the threshold value

chosen, and secondly, on the continuity of intensity over the entire edge. Indeed, an increase in the threshold value is synonymous with a better result. However, when the image edge is irregular in terms of pixel intensity along the boundary, the elevation of the threshold value will alter its closure by making it discontinuous (Fig. 2f). Unlike the other cases, those figures (Fig. 2.c, h and i) have closed and unique edges. To achieve a good result there must be a balance between the continuity and uniqueness of the edge.

2.2.2. 3D-CAD modeling of the bony elements

All results in the different steps in the process of reconstruction are illustrated in Figs. 3 and 4.

During the process of 3D-CAD modeling of the bony element (femur of the 2nd Patient), after the step of noise filtering, the scatter undergoes triangulation giving a surface mesh that has holes (Fig. 3b). These holes are due to the non-selection of certain points belonging to the scatter. After filling the holes (Fig. 3c), the mesh is smoothed by increasing the number of triangles. From the resulting refined mesh (Fig. 3d), parametric curves are created to compensate for irregularities

Fig. 3 – Reconstruction of 3D-CAD model of the patient's 2 femur and tibia.

Fig. 4 – Finite Element Analysis of the Femoral Implant and the PE insert.

in the mesh. Then a smoothing of the curves is done to reconstruct the 3D-CAD model.

The values shown in Tables 1 and 2 justify the good reproducibility of 3D-CAD models, where we note that the deviations curves-mesh are respectively the maximum and minimum (0.67 mm and 0.00 mm), and those surfaces-mesh are (6.69 mm and –8.61 mm) respectively. The average deviations are of the order of tens of microns.

3. Finite element analysis of TKP issued from the reconstructed model

3.1. Extraction of the knee prosthetic implants

The study is focused on a posterior preserved prosthesis. During the design and the extraction of the prosthetic implant

models, the adaptation is made to bring as close as possible the outer surfaces of the implant to the 3D-CAD model of the bone.

For the femoral implant, the geometries of the different parts are defined following a standard diagram of the femoral implant ranges.⁸

Table 1 – Analysis of deviations for the 1st patient.

Patient I	Curves-mesh		Surfaces-mesh	
	Femur	Tibia	Femur	Tibia
Maximal deviation (mm)	0.6707	0.6782	2.6003	6.6917
Minimal deviation (mm)	0.0000	0.0000	–1.269	–8.614
Average deviation (mm)	0.0787	0.0576	0.0537	0.0284
Standard deviation (mm)	0.0853	0.0731	0.2219	0.5440

Table 2 – Analysis of deviations for the 2nd patient.

Patient 2	Curves-mesh		Surfaces-mesh	
	Femur	Tibia	Femur	Tibia
Maximal deviation (mm)	0.6274	0.6461	0.9187	2.9648
Minimal deviation (mm)	0.0000	0.0000	–2.618	–6.660
Average deviation (mm)	0.0658	0.0738	0.0467	0.0621
Standard deviation (mm)	0.0793	0.0797	0.2079	0.2880

The shape and dimensions of the PE insert depend jointly on the shape of the tibia and the dimensions of the femoral implant. The cavities of the PE insert are obtained from the surface from three elliptical sketches, one central allowing the flexion/extension movement of the knee and the two others are at 30° and 40°, respectively providing both internal and external rotations of the knee. The geometry of the base of the tibial tray corresponds to that of the lower part of the PE insert.

In the assembly, the bone cuts are made on both parts; femur and tibia and must correspond to the size of the implants inserted.

3.2. Finite element analysis of the femoral implant and the PE insert

The static analysis by the finite elements of both prosthetic implants (PE insert and femoral implant) is made under the module Cosmos Works of Solid Works. The objective is to determine the distribution of stresses, displacements and deformations in these components during a normal gait cycle (<http://www.gla.ac.uk/ibls/fab/tutorial/anatomy/hfgait.html>) by simulating different positions (flexion angles) of the femur relative to the tibia namely 0°, 15°, 30°, 45° and 60°.

3.2.1. Method of analysis

The two important movements considered are the flexion and extension because they are the two main movements that undergoes in the knee during normal walking.

Our study covers only the position phase of the gait cycle, since in the oscillation phase, the stresses present in the knee joint are very low and generally distributed over the muscles and ligaments.

For the femoral implant, only the movement in the direction of the axis of the tibia is permitted, the movements in the directions of the transversal axis and the anterior/posterior axis are fixed. On the other hand, the PE insert is fixed in all directions and the knee is assumed in normal alignment.

The contact forces in the knee joint are chosen corresponding to the different angles of flexion/extension.

The biomaterials of the implants used are considered linear elastic and isotropic, and their mechanical properties are given in Table 3.

The coefficients of friction between the femoral component and the PE insert and between the tibial tray and the PE insert are “0.04”⁹.

With these models, five different phases of the flexion angle 0°, 15°, 30°, 45° and 60° of the gait cycle are simulated. At each loading step, the PE insert is fixed and an axial load is applied vertically to the femoral component. The vertical

Table 3 – Mechanical properties of biomaterials used for the implants.

Component	Material	E (GPa)	Poisson's ratio
Femoral implant	(Cr–Co–Mo)	200	0.3
PE insert	HDPE	1.07	0.4101
Tibial tray	Ti–6Al–4V	104.8	0.31
Femur and Tibia	Bone	170	0.3

loads 500N, 800N, 1300N, 1800N and 2300N are applied at 0°, 15°, 30°, 45° and 60° of the flexion angle.

3.2.2. Analysis results

With the finite element models of implants considered, the distributions of stress, deformations and displacement were simulated for different states of flexion by varying the angle and the loading. The results of the maximum values of Von Mises stresses, displacements and deformations are scored in Table 4.

The (Fig. 4) represent the results of the distribution of Von Mises stresses, displacements and deformations respectively in the femoral implant and PE insert for a few angles of knee flexion.

3.2.3. Discussion of results

According to the results of the finite element analysis of the two components, it is clear that the increase in torque values (force/flexion angle) induces an increase in Von Mises stress also in the displacements and deformations at the contact areas (Table 4). In fact, since both compression and tension occurs at the contact surfaces and are conjugated the contact points on the surfaces of both components will be subjected to these forces.

If the load carried by the prosthesis is larger, the effects in the interfaces (bone/femoral component and the femoral component/Insert PE) will be greater. The contact resistance due to the load resulting from the direct compression of the polyethylene and the tensile effects in the periphery of the contact area, this gives rise to higher stresses at the contact surfaces (Fig. 4h and i).

On the other hand, the increase of the flexion angle tends to accentuate the effect of the tensile forces, increasing the contact surface of the PE insert, resulting in a more elliptical shape (Fig. 4h and i).

It is also noted that the location of the stress concentration on each surface of the PE insert moved posteriorly as flexion proceed from 0° to 60° (Fig. 4h and i).

The geometry of the contact surfaces between the femoral component and the PE insert considered in our study is such that the joint surfaces are more consistent in a medial–lateral direction (Fig. 4h and i).

4. Conclusions

In this article, we developed two separate subjects.

In the first particular attention was paid to the CAD model of the two components of the knee joint (femur and tibia), using a moderate and rational methodology ensuring consistency with the 3D reconstruction of the knee joint. The

Table 4 – Maximum results of Von Mises stresses, displacements and deformations.

Component	Max values	500N 0°	800N 15°	1300N 30°	1800N 45°	2300N 60°
Femoral implant	Stress (MPa)	52.50	66.80	99.70	121	142.2
	Displacement (μm)	19.09	33.56	49.69	64.70	84.15
	Deformation (*10 ⁻⁴)	2.87	2.97	3.37	4.07	5.22
PE Insert	Stress (MPa)	1.20	1.60	2.20	2.90	3.4
	Displacement (μm)	5.21	7.11	9.58	11.39	12.69
	Deformation (*10 ⁻⁴)	1.10	1.12	1.52	2.47	2.50

biomechanical and medical applications of this model are many and varied. However, this work is still preliminary, but the results promise to significantly improve performance and reduce construction time.

In the second topic, our focus was on the design of implants adapted to both the specific ranges of implants available in the literature and the reconstructed 3D-CAD models. Until now, few numerical models of TKP were developed. Given its importance, today there is increased attention and emphasis in literature proposing more realistic improved models.

Furthermore, FE analysis of TKP implants provide us information about their behavior vis-à-vis the loads and flexion angles during a gait cycle and helped us locate and characterize areas of stress concentrations especially in the PE insert, thus expanding our knowledge of its mechanical behavior.

Conflicts of interest

The author has none to declare.

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