Title:
Recreation of the Movements of the Femur and the Pelvis 3D Prototypes, Using a Computerized Axial Tomography (CAT) to Perform the Geometric Process

Authors:
Dina Rochman, drochman@correo.cua.uam.mx

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Introduction:
In this work, we present the research carried out on the Campus of the Autonomous Metropolitan University of Cuajimalpa in Mexico City, whose objective is to design, from the perspective of descriptive geometry a mechanical joint to recreate the rotation movements of the femur and pelvis.

In the CAT scan, the femur and pelvis were segmented to create the STL, OBJ and DWG files. And in the geometric process, several computer programs were used to reduce the number of faces in the mesh and perform 3D modeling and printing.

Whit the present study we demonstrate that it is possible to recreate, using a spherical mechanical joint with a pivot the movements of abduction/adduction, flexion/extension and internal/external rotation of the femur and, the anteversion and retroversion movements of the pelvis of human body in a 3D prototype. Therefore, we conclude that the methodology presented in this study can be applied in the development of a 3D biomechanical model of the bone system.

Main Sections:
The set of all the bones of the human body make up the skeletal or bone system. Of the bone system, the bones that interest us this study are the femur and the pelvis. The femur in its upper part has the femoral head, femoral neck, greater trochanter and lesser trochanter (Fig.1 (a)). In addition, the pelvis contains the following bones: sacral and coccyx and three pelvic bones (hip): ilium, pubis and ischium (Fig.1 b)).

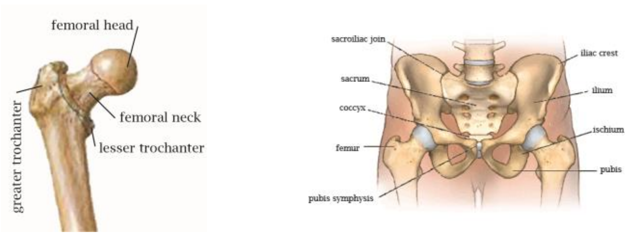

Fig. 1: (a) Upper parts of the femur, and (b) Pelvis parts.

An important component in the bone system is the joints, which are the point of contact of two bones in the body, which allow certain types of movements.

Since 1895 when Wilhelm Röntgen discovered X-rays, technology has had a crucial role when researching of the human body. Among the latest technologies developments we can count computed tomography (CAT), which is a digital geometry processing that is used to generate a three-dimensional volume of the interior of the body from a small series of two-dimensional radiographic images taken around a single axis of rotation [3].

In his thesis Dr. León (et al. 2015) [2] mentions that among the researchers who used this technology to generate a 3D model are Keyak (1990) who presented a method based on “property arrangements”. Marom and Linder (1990) reconstructed cross sections of a pixel by pixel tomography. In 1998, Kullmer developed subroutines where each pixel represents a finite element. Also in 1998, Viceconti proposed an image acquisition methodology for bone modeling using the FEM. Other authors such as Zannoni in 1998 developed algorithms to generate meshes and the acquisition of mechanical properties. Kernes, in 1999, built a 3D model of finite elements based on densitometry. In addition, in 1999 Van Rietbergen built a model of the proximal part of a canine femur using micro tomography.

In our study, we used the CAT technology to segment the femur and pelvis to recreate their rotational movements in a 3D prototype.

<u>Methodology:</u>

For the methodology we carried out in our study, we consider what software allows us to import the STL, OBJ and DWG files to perform the necessary actions to model, save and create the 3D prototype (Fig. 2).

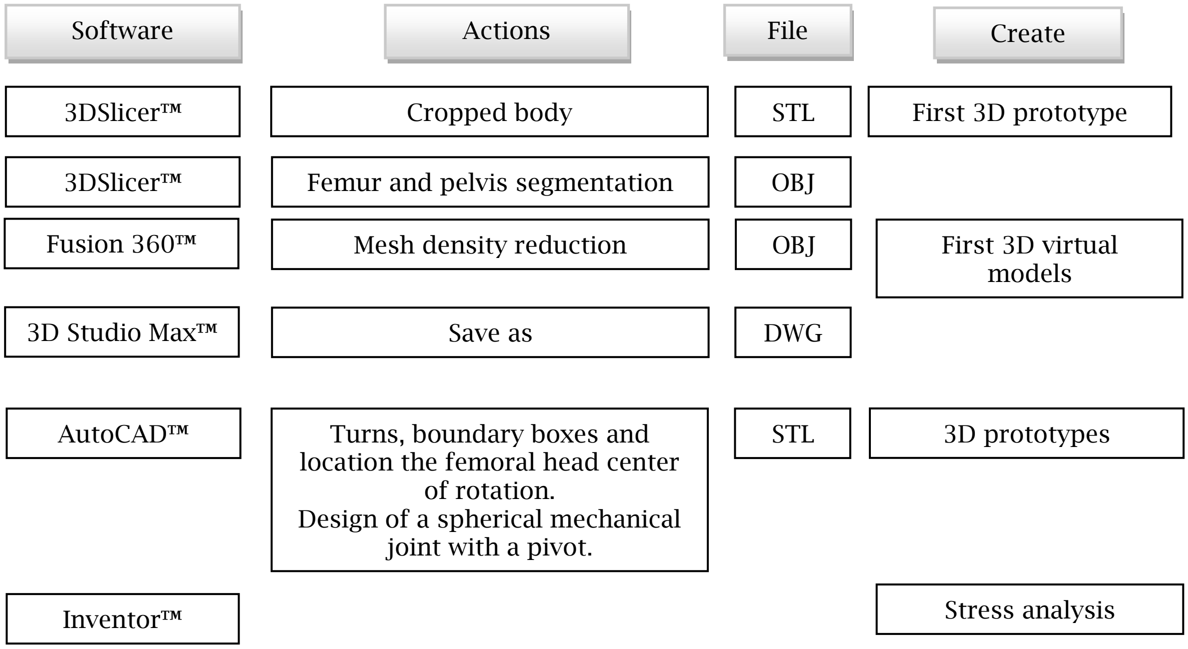

Fig. 2: Methodology to model and build the prototype.

The process that was carried out to print the first prototype was as follows: in the 3DSlicer™ program [1] the 266 images were loaded and the person's 3D model was opened; the view of the 3D model was changed to bones, the 3D model was cut to delimit the parts to be studied, the femur and the pelvis, and each of the parts were labeled green (Fig. 3 (a)). The STL file was created and the first prototype was printed (Fig. 3 (b) and (c)).

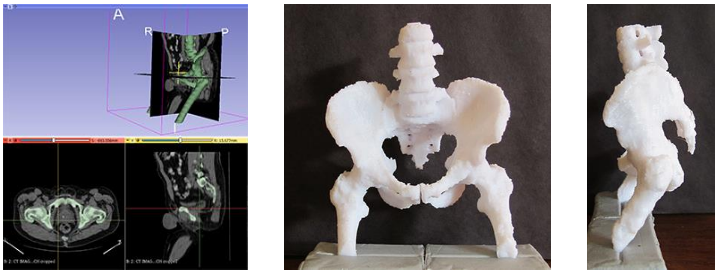

Fig. 3: (a) 3D cropped model, and (b and c) 3D prototype.

To independently recreate the movements of the femur and pelvis, each of the parts was segmented by cutting the 3D model and were labeled with different colors: green for the pelvis and yellow for the femur. After filling up the medullary cavity of each part in each image to avoid hollows, the file was saved with the extension OBJ.

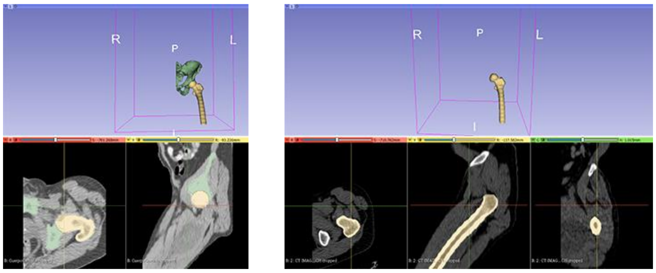

Fig. 4: (a) Segmentation of the femur and the pelvis, and (b) Femur view.

The OBJ file was opened in Fusion 360™. In this software, the density of the mesh was reduced from 0.25 to 0.10 since the mesh was very dense. The virtual 3D model (Fig. 5) was created to confirm that the segmentation of the parts was carried out correctly.

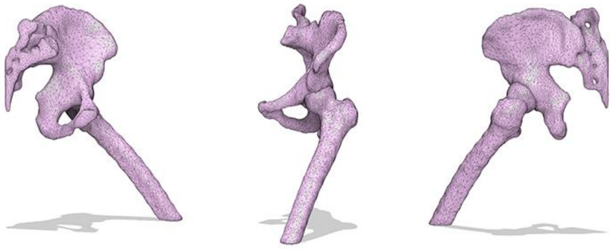

Fig. 5: 3D virtual models.

Unable to open the OBJ file in the AutoCAD™ software, the 3D Studio Max™ software was used to save the file with the DWG extension. When we open the DWG file in the AutoCAD™, solids appear in a horizontal position (the patient lying down) (Fig. 6 (a)). To place the solids in an upright position (the patient standing) we trace the bounding boxes of each of the solids and rotate them 30° independently (Fig. 6 (b)). We trace the bounding box around the femoral head, considering its size and shape from the segmentation that was done previously, and from its center we modeled a sphere with a diameter of 21.78 mm (Fig. 6 (c)).

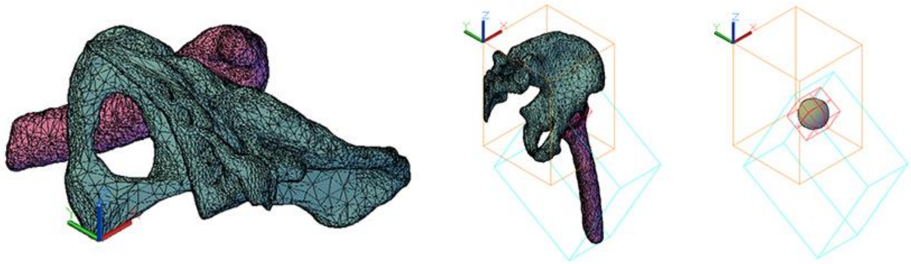

Fig. 6: (a) Horizontal position of solids, (b) Vertical position of solids within the bounding box, and (b) Sphere.

Design and stress analysis of the spherical mechanical joint with a pivot:
For the joint design, the challenge was to find a way to connect the femur with the pelvis and make each part rotate independently. The movement of the femur is with three degrees of freedom and the movement of the pelvis is with one degree of freedom. Therefore, we decided to attach a pivot to a spherical mechanical joint to connect the two solids so that we could rotate them independently. In addition, we had to figure out how to insert the femoral head into the joint, preventing it from coming out in order to recreate the rotational movements of the femur.

After performing several tests, the spherical mechanical joint was created as follows. We hollowed out the sphere, preserving 19 mm thickness. To avoid the sphere from intersecting with the femoral neck, we cut the sphere at a height of 14.79 mm. At the height of 2.79 mm we segment the sphere at every 30˚, generating six equal parts. Finally, the pivot was modeled and attached to the joint (Fig. 7 (a) and (b)).

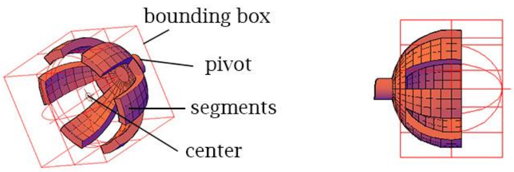

Fig. 7: Spherical mechanical joint: (a) Isometric view, and (b) Frontal view.

Joint stress analysis was simulated in the Inventor™, using a force of 4,903N at the bottom of two segments and six constraints at the 2.79 mm height of the joint. The results show that the maximum stress took place at the beginning of the segments and that these could break because of the 35.9Mpa the elastic limit of the PLA (Figure 8 (a)). The displacement of the lower part of each of the segments is 0.5435 mm (Figure 8 (b)). The displacement that is needed to introduce the femoral head into the joint is 0.25mm, so we would have no problem. A safety factor greater than 1 indicates that the material is essentially elastic, so we conclude that the joint design is acceptable, since it will not permanently deform (Figure 8 (c)).

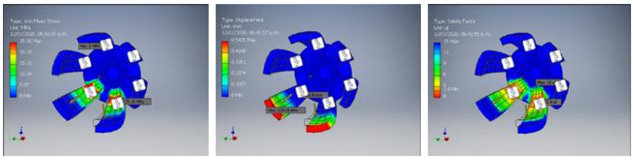

Fig. 8: Stress analysis of the joint: (a) Maximum stress, (b) Displacement and (c) Safety factor.

Femur and pelvis movements from solids:

In AutoCAD™ we performed the simulation of some rotational movements of the femur considering as a support point the center of the femoral head, which is also the center of the joint, and the rotational movements of the pelvis in the sagittal plane at 90˚ and 15˚ (Figure 9).

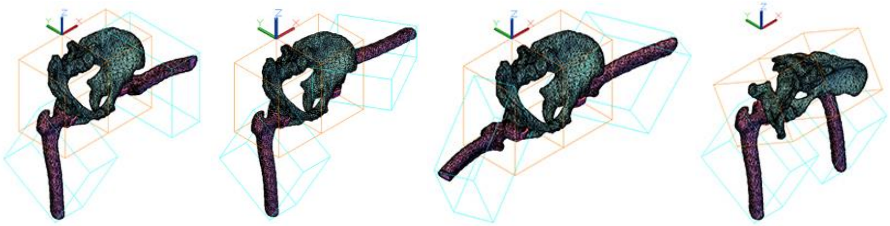

Fig. 9: Movements: (a) Flexion movement of the femur at 120˚, (b) Abduction movement at 90˚, (c) Abduction movement at 70˚, and (d) Anteversion movement of the pelvis at 90˚.

Movements of the femur and pelvis from 3D printing:

Although Figure 10 (a, b, c, and d) shows some of the rotational movements of the femur and pelvis recreated in the 3D prototype, we can say that all the aforementioned rotational movements are feasible in the 3D prototype.

Fig. 10: 3D prototype: (a) Abduction movement of the femur at 90˚; (b) Flexion movement of the femur at 90˚; (c) Anteversion movement of the pelvis at 90˚ and (d) Abduction movement of the femur at 70˚.

In the 3D prototype, the femoral head rotates inside the joint without any problem because the center of the joint as the center of the femoral head, are always at the same point. In this case, a minimum tolerance between the two parts was left to avoid friction. The femoral head stays put inside the joint because, by not leaving tolerance between the pelvis and the joint, the pelvis applies pressure in the joint.

Conclusions:

Descriptive geometry goes back to antiquity, but with the technological advances nowadays in addition to modeling any object we can turn it into a 3D prototype with movement. Therefore, we conclude that the method presented in this study will serve to change the technological paradigm in both research and teaching-learning.

REFERENCES:

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[2] León, M. D.: Determination of the structural rigidity of a human femur by FEM, Ph.D. Thesis, Faculty of Engineering National Autonomous University of Mexico, University City, 2015.

[3] https://en.wikipedia.org/wiki/CT_scan, CT scan.