



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

Dina Rochman 

Universidad Autónoma Metropolitana Cuajimalpa, drochman@correo.cua.uam.mx

Corresponding author: Dina Rochman, drochman@correo.cua.uam.mx

Abstract. 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 recreate, from the perspective of descriptive geometry, the rotational movements of the femur and pelvis using a mechanical joint. 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. With 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 the 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.

Keywords: Femur, Pelvis, CAT, Geometric process, Joint, Rotational movements, Rapid Prototyping.

DOI: <https://doi.org/10.14733/cadaps.2021.519-531>

1 INTRODUCTION

Leonardo da Vinci began to carry out in Milan his anatomy studies between 1514 and 1515, but it was in France that he deepened the study of man with the intention of discovering the mechanisms that regulate his functions and movements.

In 1543 Andreas Vesalius (1514-1564) published "De Humani Corporis Fabrica". This text is divided into seven books or sections with the following content: "In the first book I have explained the structure of all the bones and cartilage that must be known in the first place by anatomy studies..." [5].

Anatomy is the science that studies the structure of living beings, that is, the arrangement of bones and organs and the relationship between them. 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 in this study are the femur and the pelvis.

The femur is the largest and strongest bone in the human body and articulates in the upper part with the pelvic bone. The femur has two main functions: the first is to act as a support structure, allowing the body weight to be transferred from the hip joint to the knee joint; the second is to act as a rigid structure, allowing the muscular action to produce movement in the hip and knee joints [7]. The femur in its upper part has the femoral head, the femoral neck, the greater trochanter and the lesser trochanter (Figure 1 (a)).

The pelvis is a bowl-shaped structure that supports the spine and protects the abdominal organs [3]. The pelvis contains the following bones: sacrum and coccyx and three pelvic bones (hip): ilium, pubis and ischium (Figure 1 (b)).

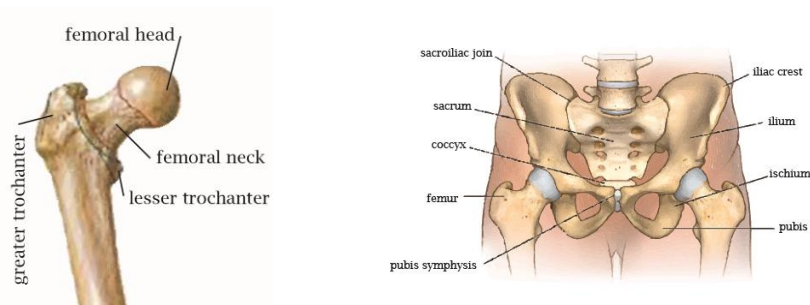


Figure 1: (a) Upper parts of the femur, and (b) Pelvis parts.

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 technology 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 [8]. It is worth mentioning that the 1979 Nobel Prize in Physiology or Medicine was awarded jointly to Allan M. Cormack and Godfrey N. Hounsfield "for the development of computer-assisted tomography".

In his thesis, Dr. León (et al. 2015) [4] 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 represented 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 finite element 3D model based on densitometry. In addition, in 1999 Van Rietbergen built a model of the proximal part of a canine femur by micro tomography.

In our study, we used high-resolution computerized axial tomography images to segment and recreate rotational movements of the femur and pelvis in a 3D prototype. Wherein, the density resolution in CAT refers to the accuracy of the average attenuation coefficients calculated for each voxel and expressed in CAT number or in gray density in the corresponding pixel.

This article is organized as follows: in section 2 we explain the methodology we used to carry out the whole process, in section 3 we explain the process that was carried out to create the first 3D prototype; in Section 4 we explain the process followed from the segmentation of the femur

and pelvis to the DWG file; Section 5 presents the design of the spherical mechanical joint and its stress analysis. The results are presented in section 6, and finally in Section 7 the conclusions are presented. We want to mention that all the figures in this document are original and created by the author at the Metropolitan Autonomous University Campus Cuajimalpa in México City.

2 METHODOLOGY

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

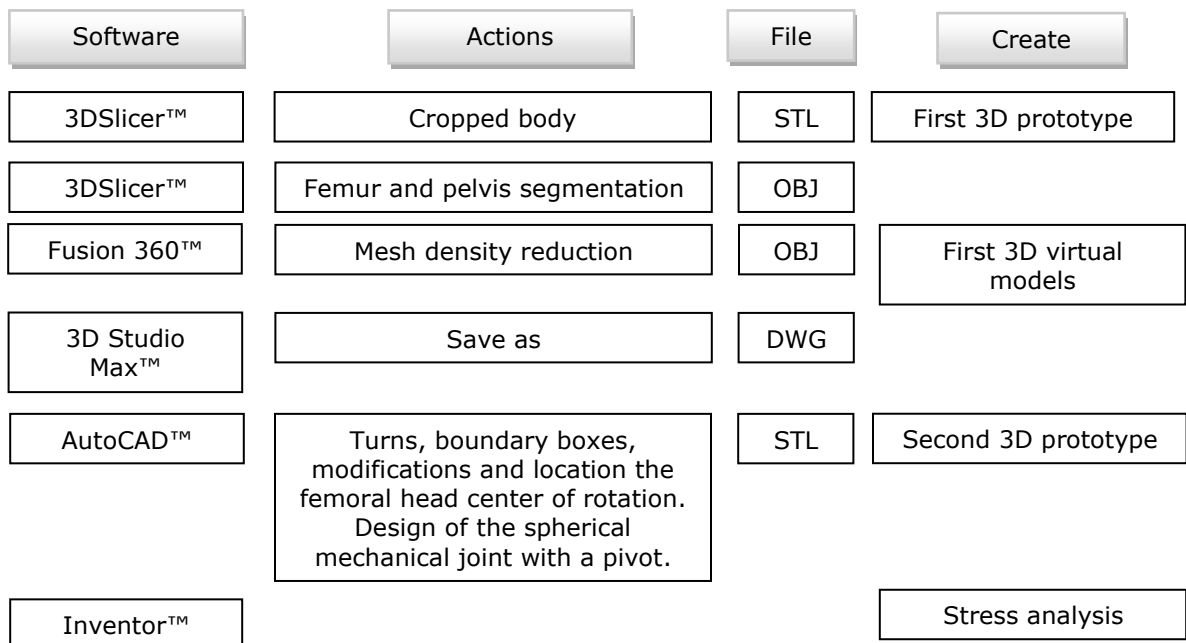


Figure 2: Methodology to model, save and create the 3D prototypes.

3 FIRST 3D PROTOTYPE

The images of the DICOM (Digital Imaging and Communication in Medicine) format with which we work belong to a man, due to confidentiality, we cannot give more information.

The process that was carried out to print the first prototype was as follows: in the 3DSlicer™ program [2] the 266 images were loaded and the person's 3D model was opened (Figure 3 (a)); the view of the 3D model was changed to bones (Figure 3 (b)), the 3D model was cut to delimit the parts to be studied, the femur and the pelvis (Figure 3 (c)) and each of the parts were labeled green (Figure 3 (d)). The STL file was created and the first prototype was printed (Figure 3 (e) and (f)).

At the bottom of Figure 3 (d), the part of the medullary cavity of the femur and the pelvis are not entirely painted green. This indicates that both the femur and the pelvis will be hollow in 3D printing.

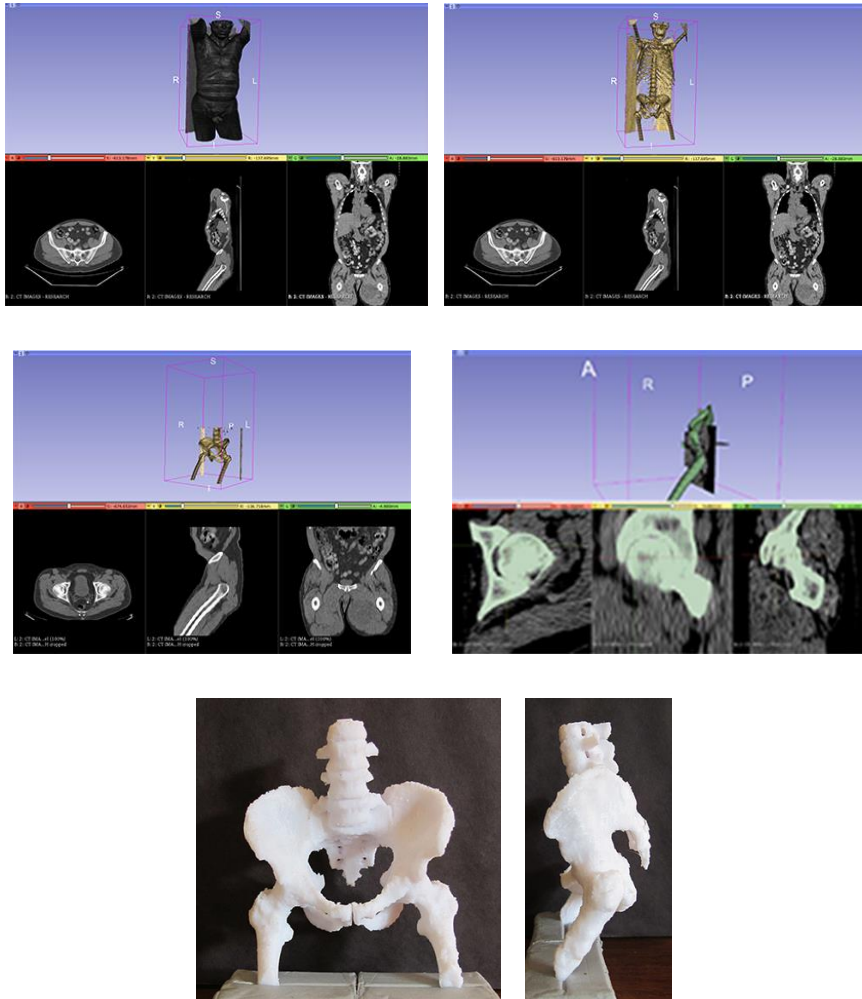


Figure 3: Process that was carried out to print the first prototype: (a) 3D model of the person, (b) View of the bones, (c) Delimitation of the femur and pelvis, (d) Labeling of the parts and (e an f) 3D printing.

4 FROM THE SEGMENTATION OF THE FEMUR AND PELVIS TO THE DWG FILE

To independently recreate the movements of the femur and pelvis, each of the parts was segmented by cutting the 3D model (Figure 3 (c)) and were labeled with different colors: green for the pelvis and yellow for the femur.

The segmentation process was carried out as follows: first the femoral head was delimited and segmented to separate it from both the femur and the pelvis (Figure 4 (a) and (b)), then the entire femur joined to form a single unit (Figure 4 (c)). After filling up the medullary cavity of each part in each image to avoid hollows (Figure 4 (d)), the file was saved with the extension OBJ.

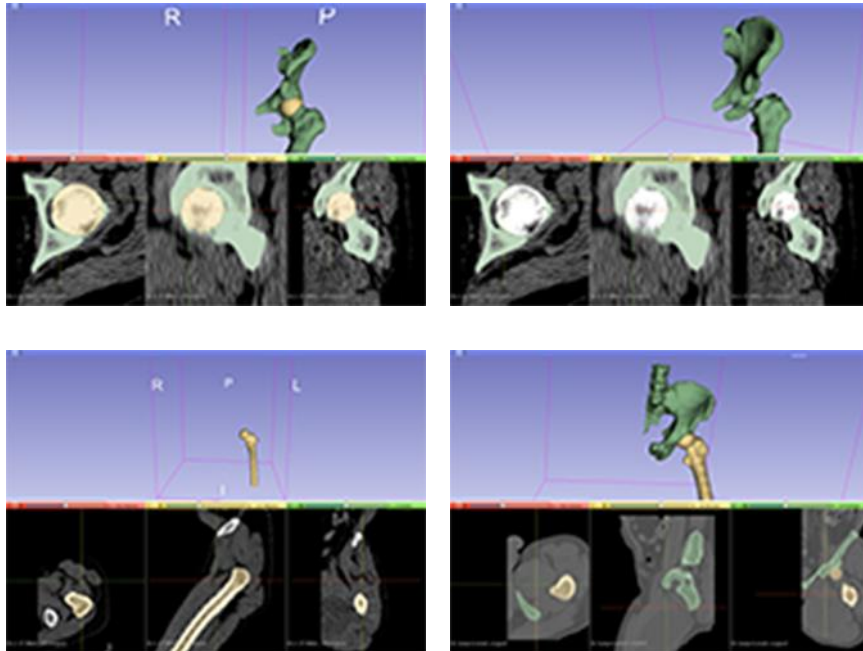


Figure 4: Segmentation of the femur and pelvis: (a) Segmentation of the head of the femur, (b) Separation of the femur and pelvis, (c) Union of the femur and (c) Independent parts.

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

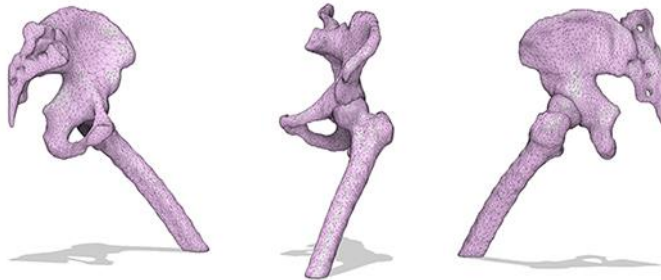


Figure 5: 3D virtual models.

5 DESIGN OF THE SPHERICAL MECHANICAL JOINT AND ITS STRESS ANALYSIS

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 AutoCAD™, solids appeared in the horizontal position (the patient lying down) (Figure 6 (a)). To place the solids in an upright position (the patient standing) we trace the bounding boxes of each solid and rotate it 30° independently (Figure 6 (b)). We trace a bounding box around the femoral head, considering its

size and shape from the segmentation that was done previously (Figure 6 (c)), and from its center we modeled a sphere with a diameter of 21.78 mm (Figure 6 (d)).

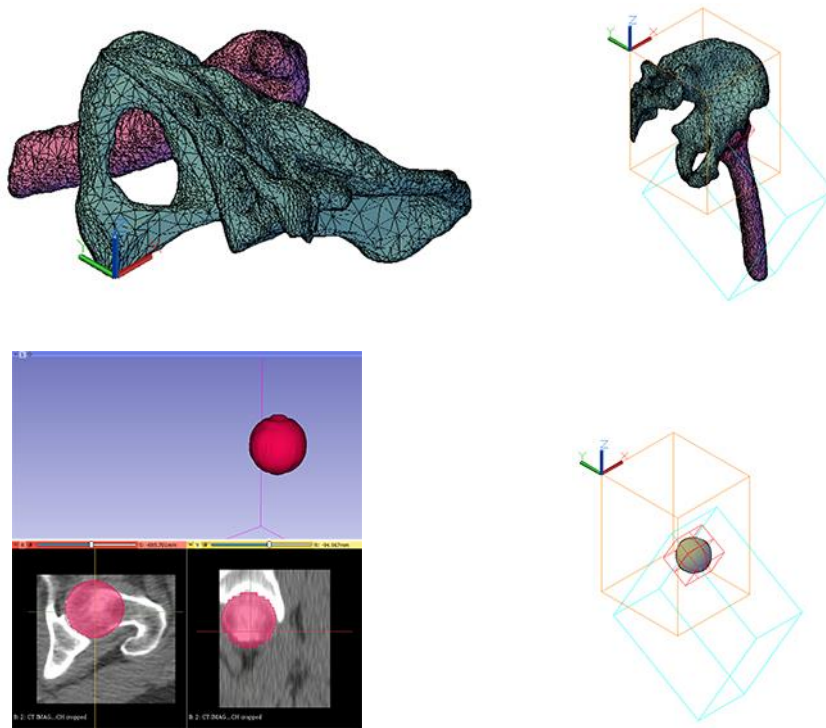


Figure 6: (a) Horizontal position of solids, (b) Vertical position of solids within the bounding box, (c) Segmentation of the femoral head and (d) Sphere within the bounding box.

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 has three degrees of freedom and the movement of the pelvis has 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. It should be mentioned that, if the hollow sphere was complete, the femoral head could not be introduced in the joint. Finally, the pivot was modeled and attached to the joint (Figure 7).

For the 3D print we used PLA (poly lactic acid). This material is more rigid than ABS, with a modulus of elasticity of 3.63GPa, which helps to avoid deformations and makes it a less elastic material. The Shore hardness (scale that measures the hardness of plastics) of PLA is 63.5, being greater than that of ABS [1].

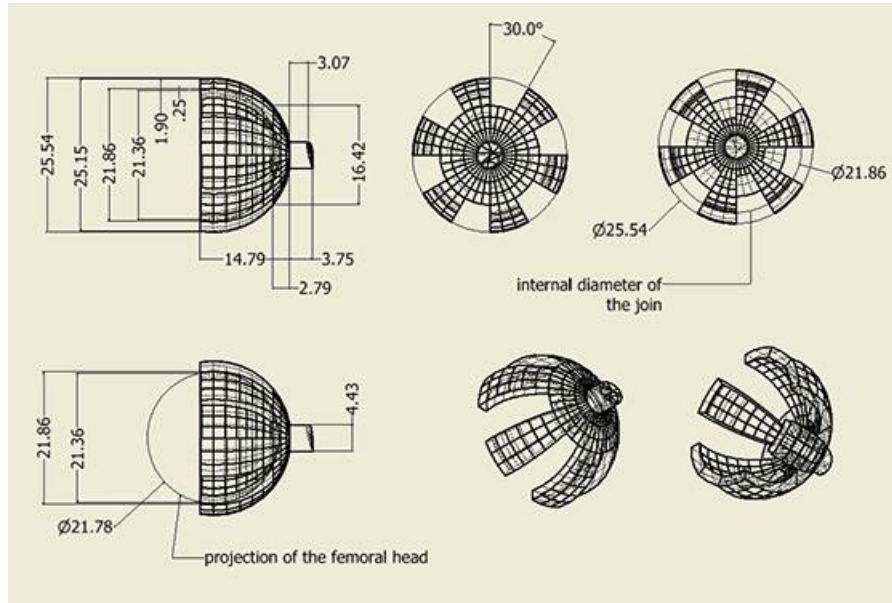


Figure 7: Dimensions of the spherical mechanical joint with a pivot.

Joint stress analysis was simulated with Inventor™, using a force of 4,903N at the bottom of two segments and six constraints at a 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 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 (Figure 8 (c)) indicates that the material is essentially elastic, so we conclude that the joint design is acceptable, since it will not be permanently deformed.

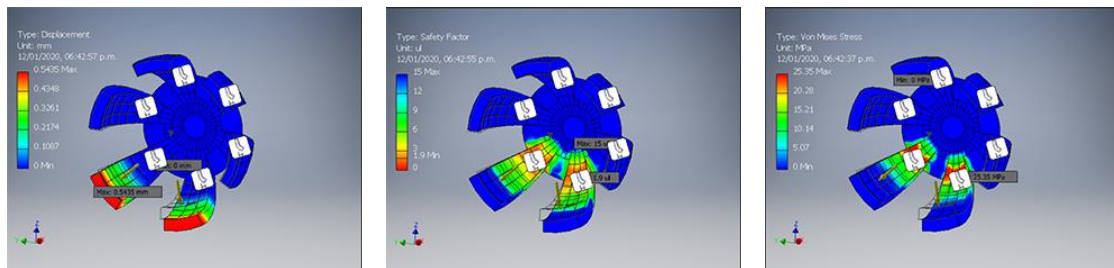


Figure 8: Stress analysis: (a) Maximum stress, (b) Displacement and (c) Safety factor.

6 RESULTS

Having as reference the anatomical posture of the human body, perpendicular to the center of gravity, three planes are linked: the sagittal plane, which divides the body into left and right; the frontal plane, which divides the body into front and rear; and the transverse plane, which divides the body by the lower and upper part (Figure 9).

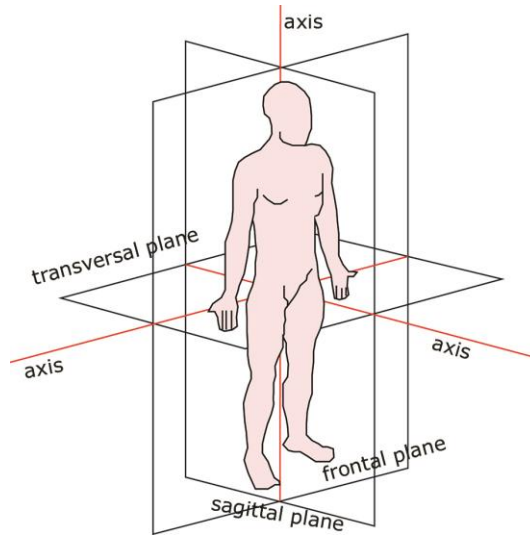


Figure 9: Planes and axis.

Regarding the mobility of the body three categories are recognized: uni axial, biaxial and multi axial, which are all are related to the mobility that bones have in relation to the joints. The axial joint has only one axis and allows movement in a single plane. The biaxial joint has two axes and allows movement in two different planes and, finally, the multiaxial joint allows movement in three or more planes.

Within the complexity of the human body, different types of movements can be pointed out: flexion, extension, abduction, adduction, rotation, circumduction, supination, pronation and displacement.

The rotational movements of the femur are: flexion/extension in the transverse axis; abduction/adduction in the posterior anterior axis, and internal/external rotation in the vertical axis (Table1 and Figure 10).

Flexion	Active flexion with extended knee	90°
	Active flexion with flexed knee	120°
	Passive flexion with flexed knee	140°
	Passive flexion with the knee extended	Less than the previous ones
Extension	Active extension with extended knee	20°
	Active extension with the knee flexed	10°
	Passive extension	20°
Abduction	The maximum amplitude of the adduction is	90°
Adduction	Maximum abduction of a hip	45°
	Some trained people can get an abduction of	180°

Table 1: Femur movements and angles.

The movements of the pelvis are anteversion and retroversion, that is, they rotate in the sagittal plane before 90° and after 15° (Figure 11). The specific sequences of rotation (Euler angles), which the International Society of Biomechanics recommends associated with the anatomical reference systems, are (1) flexion/ extension in the sagittal plane, (2) abduction/adduction around the transversal plane, and (3) axial rotation around the longitudinal axis of the bone.

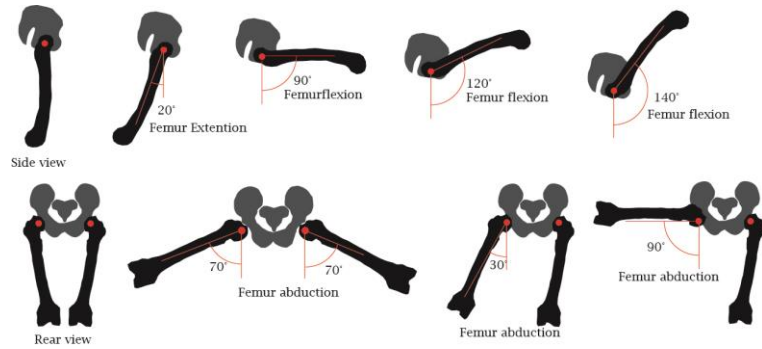


Figure 10: Illustration of the movements and angles of rotation of the femur.

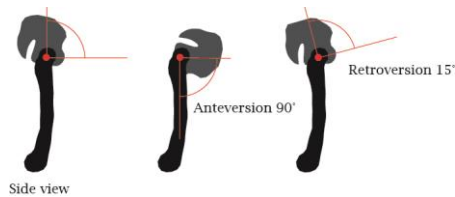
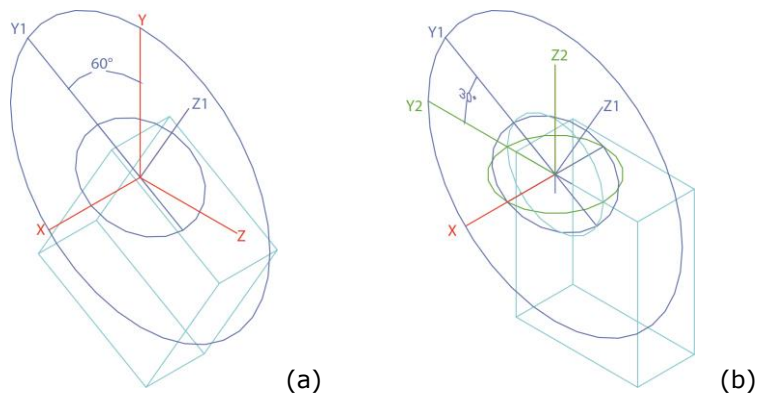


Figure 11: Illustration of the movements and angles of rotation of the pelvis.

The rotation sequence that was performed from the perspective of descriptive geometry based on the three coordinates of Euler's angles is as follows (Figure 12):

- (a) The X Y Z coordinate system was rotated around the "X" axis at an angle of 60° to have a new X Y1 Z1 coordinate system.
- (b) The X Y1 Z1 coordinate system was rotated around the "X" axis at an angle of 30° to have a new X Y2 Z2 coordinate system.
- (c) The X Y2 Z2 coordinate system was rotated around the "Y2" axis with an angle of 40° to have a new X2 Y2 Z3 coordinate system and
- (d) The X2 Y2 Z3 coordinate system was rotated around the "X2" axis with an angle of 60° to have a new X3 Y3 and Z4 coordinate system.



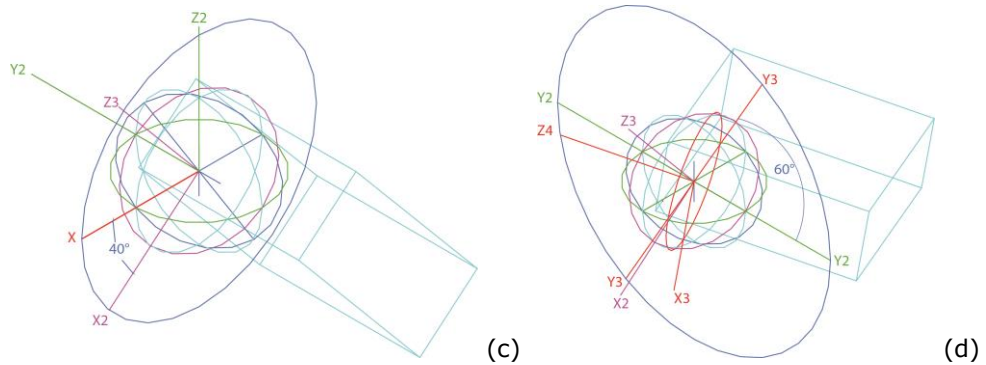


Figure 12: Femur rotation sequence.

According to the positions of the geometric figures with respect to the orthogonal projection, the femur is in a vertical position, in the first turn the femur changes to the inclined position in the lateral plane and in the last two turns the femur remains in the oblique position (Figure 13).

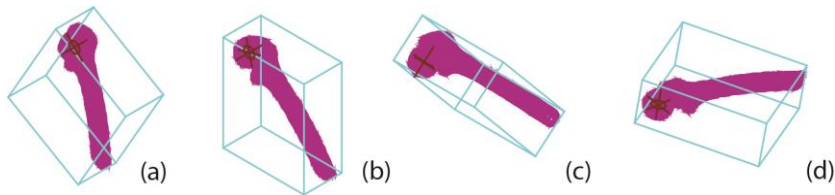


Figure 13: Position of the femur with respect to the orthogonal projection: (a) Vertical, (b) Inclined in the lateral plane, (c) Oblique and (d) Oblique.

In AutoCAD™ we performed the simulation of some rotational movements of the femur found in Table 1 (Figures 14 and 15) 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 16).

It is worth mentioning that to recreate the rotational movements in the simulation, the following modifications were made in the pelvis: the shape of the sphere was subtracted from the pelvis without leaving tolerance to prevent it from moving and exerting certain pressure on certain parts of the joint and a hole was drilled in the ilium in the horizontal direction, with a tolerance of 0.08 mm so that the pelvis can rotate.

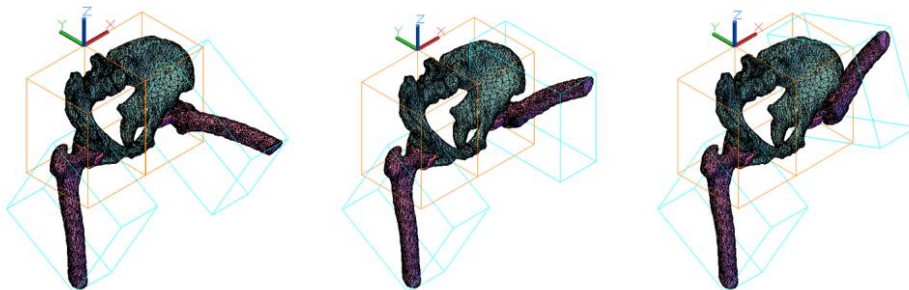


Figure 14: Flexion movements of the femur: (a) 90° , (b) 120° and (c) 140° .

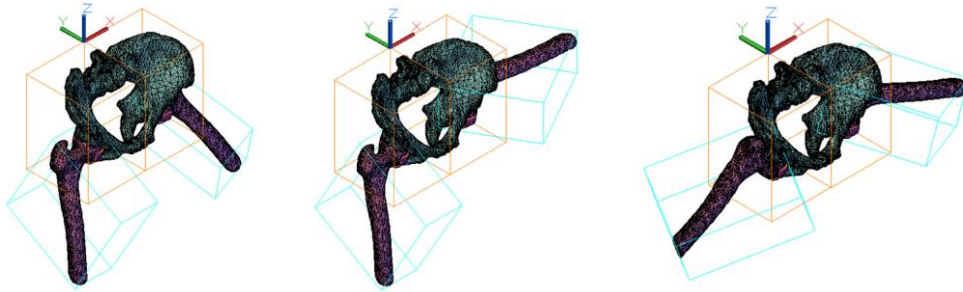


Figure 15: Abduction movements of the femur: (a) 30°, (b) 90° and (c) 70°.

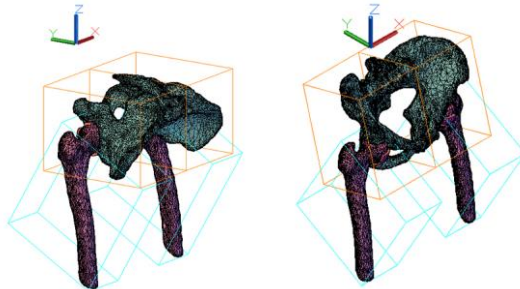


Figure 16: Rotational movements of the pelvis: (a) Anteversion 90° and (b) Retroversion 15°.

After corroborating the rotational movements of the two parts in the simulation, we printed a segment of the femur and pelvis and the joint (Figure 17 (a), (b) and (c)) to verify the rotational movements of both the femur and the pelvis in the transverse, posterior and vertical axes and in the sagittal plane, respectively.



Figure 17: 3D prototype: (a) Pelvis, (b) Joint placement in the pelvis and (c) Femoral head within the joint.

The results obtained in this test were satisfactory since both the femur and the pelvis rotated correctly and the femoral head did not come out of the joint, so we continued with the printing and assembly of the complete prototype (Figure 18 (a)).

Although Figure 18 (b, c, d and e) shows some 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.

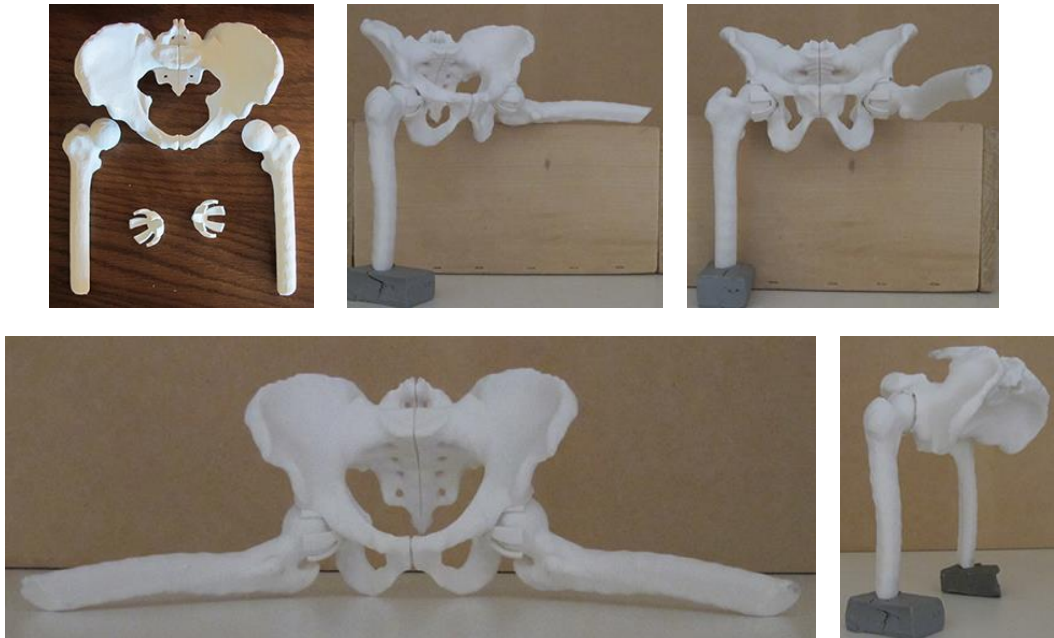


Figure 18: 3D prototype: (a) Parts, (b) Flexion movement of the femur at 90° , (c) Abduction movement of the femur at 90° , (d) Abduction movement of the femur at 70° , and (e) Anteversion movement of the pelvis at 90° .

In the 3D prototype, the femoral head rotates inside the joint without any problem because the center of the joint as well the center of the femoral head, are always at the same point. 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.

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

We consider that the technique presented in this study can be used in biomechanical studies in tandem with photogrammetry (3D motion analysis based on digital video technology), electromyography (analysis of electrical activity) and instrumented templates (recording of the pressures exerted by the foot during the walk) [6]. Since the technique presented in this study, in addition to allowing the recreation of the rotational movements of the bones, would allow other actions to be carried out with the same computer programs, such as: finding the geometric dimensions of the deformations, disorders and fractures of the bones, and ratify in a physical model the movements of a healthy body or one with some disorder.

7 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.

Dina Rochman, <http://orcid.org/0000-0001-8902-3513>

REFERENCES

- [1] Ampudia, M. C.; PLA. Material, interest and printing tips. <http://www.dima3d.com/pla-material-interes-y-consejos-de-impresion-3/>
- [2] 3DSlicer, <http://slicer.or>, Medical Image Informatics Software.
- [3] Hackensack Meridian Health: Facts about the spine, shoulders, and pelvis. http://wellnesscenter.hackensackmeridianhealth.com/Search/85_P01360
- [4] 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.
- [5] Morilla, O.: A bibliographical treasure of the history of medicine at the Complutense University: the first edition of Andreas Vesalius, "De humani corporis fabrica" (Basileae: ex Officina Ioannis Oporini, 1543), Folio Complutense, 2013. <https://webs.ucm.es/BUCM/blogs//Foliocomplutense/7149.php>
- [6] Partida, J.; Medical Biomechanics, 2017. <https://es.slideshare.net/jaimepartida/biomecnica-mdica>
- [7] Younge, A. M.: Computational and Experimental Modelling of the Femur, Ph.D. Thesis, Department of Civil and Environmental Engineering Imperial College of Science, Technology and Medicine Prince Consort Road, 2012.
- [8] https://en.wikipedia.org/wiki/CT_scan, CT scan.