Univerza v Mariboru

FACULTY OF MECHANICAL ENGINEERING

3D Modeling Of Human Knee And Movement Simulation

Diploma work

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Acknowledgements

Thanks to all my family for their unconditional support
Especially dedicated to my mother Tere and my father Angel

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List of abbreviations

DOF: Degrees of freedom

MCL: Medial collateral ligament

LCL: Lateral collateral ligament

ACL: Anterior cruciate ligament

PCL: Posterior cruciate ligament

DICOM: Digital Imaging Communications in Medicine

PCF: Patellar Compression Force

CAD: computer-aided design

SLA/SL: stereolithography

1. Introduction

1. Motivation

One of the most distinguishing factors characterizing the human being is the way of displacement. The gait, the action of locomotion by moving the inferior limbs, made a huge and well-known influence in human evolution, when it went from quadruped to bipedal gait.

It was an adaptive change that came with great advantages like bigger visual field, freedom of upper limbs for many purposes like transport, less use of energy, less surface exposed to sun, etc.

Because if its structure and position, the knee is one of the biggest and more complex joints in the human body, with a particular working difficult to understand. Such is this, that the most basic models of biomechanics applied only few years ago were far distant from reality.

The loose of mobility in this joint can happen because of injuries, deformities or illnesses due to swelling or advanced age. When this occurs, a replacement by prosthesis can be performed in order to improve the quality of life of the subject.

Because of this, it´s necessary to do studies about the movement of the knee, to understand it better, being able to develop prostheses with better functionality, more adapted to the natural human gait.

1.2 Objectives

The main objective of this work is to obtain a 3D model the bones and main ligaments of a human knee, from a CT-scan, and then make a kinematic simulation to determine the movement of the three parts involved, femur tibia and patella, when the knee moves in flexion/extension.

Towards this, study the whole human leg as a mechanism and the knee as well, the tendons and ligaments, from a structural point of view.

1.3 Short description of diploma work

The work consists in obtaining a 3D model of significant parts of a human knee from a CT-scan in form of DICOM file. Then an .stl file is obtained for each part (bones and ligaments). This is performed with a DICOM analysis program (3D Slicer). After this, the .stl file is imported it with a CAD program (Solidworks), to obtain a movement simulation.

2. Present state of the art

The stereolithography (SLA or SL), also known as optical fabrication, photo-solidification, is an additive manufacturing or 3D printing technology used for producing models, prototypes and production parts up one layer at a time by curing a photo-reactive resin with a UV laser or other similar power source.

Stereolithographic models have been used in medicine since the 1990s, for creating 3D corporeal models of various anatomical regions of a patient, based on datasets from CT-scans, RMI, ultrasound, or any other medical image technique.

Medical models are used in medicine, dental industry and surgery to provide surgeons with a better appreciation of the anatomical situation of the patient before surgery, and also for prosthesis custom design and manufacture. Although the improved 3D computer reconstruction and virtual surgical planning means that models in some cases are not needed, only remains for complex surgeries and prosthesis planning.

There are several specialized companies that provide medical modeling service, like PRD in the UK, Medical Modeling Inc. in the USA and Materialise, in Belgium.

The applications of 3D modeling and printing are not only in medicine. In fact, it is used in architecture, construction, industrial design, automotive, aerospace, military, fashion, footwear, eyewear, and many other fields.

3. Mechanical view of joints

3.1 Introduction

A joint is a point of articulation between two or more bones, specially a connection that allows motion. They are classified according to structure and movability as:

- Fibrous joints

These joints are immovable. Most joints of the skull, also teeth.

- Cartilaginous joints

Slightly movable. Joints connecting vertebrae and the pubic bones.

- Synovial joints

Freely movable. Most of the joints in the body are this type allowing gliding, circumduction, rotation and angular movement. Limbs' joints.

3.2 Common parts of joints

3.2.1 Bones

The bone is the hard rigid form of connective tissue conforming the skeleton. It is composed mainly of calcium salts. The function of bones is to provide support and protection to the various organs of the body, while allowing movement between its parts.

The internal structure of bone is composed by an hard outer layer made of compact bone tissue, followed by the called trabecular bone tissue, an open cell porous network that fills the interior of the bone.

The skeleton structure is bound together by ligaments, and set in motion by muscles, which are secured to the bones by means of tendons.

Mechanical properties: The osseous tissue is relatively hard and lightweight composite material made of mineral calcium phosphate, calcium hydroxylapatite (this gives the bone its rigidity) and collagen, an elastic protein, which improves fracture resistance. Relatively high compressive strength of around 170 MPa, poor tensile strength of 104-121 MPa, and very low shear stress strength, 51,6 MPa. It is essentially brittle, but has a significant degree of elasticity given by collagen.

In a movable joint, bones act as the rigid parts of a mechanism allowing relative movement between them.

3.2.2 Ligaments

Ligaments are bands (or sheets) of tough fibrous tissue connecting two or more bones, cartilages or other structures. They serve for both supporting and strengthening of the joint, by means of holding the bones together and preventing excessive movement between parts. Their mechanical function is to guide the normal movement and prevent unusual movements.

Ligaments are flexible and slightly elastic, composed of parallel collagenous bundles. They have anisotropic behavior, and the mechanical model is viscoelastic without plastic component (viscous and elastic component parallel). Also the behavior depends on composition.

3.2.3 Tendons

Tendons are, like ligaments, bands of dense fibrous connective tissue, but unlike them these attach muscles to bones. Their mechanical function is to transmit the forces from muscles to bones.

They are made of collagenous fibers as well, with great traction resistance and ductile (absorb energy). Also anisotropic behavior, and the mechanical model is viscoelastic without plastic component (viscous and elastic component parallel as ligaments, plus an elastic component in series).

3.2.4 Condyles

Condyles are rounded protuberances at the end of bones, usually for articulation with another condylar bone. They are convex in two directions, and the bone that connects to it is concave in two directions (ellipsoid segments).

They are, like all articular cartilages, white and shiny surfaces with rubbery consistency, and slippery, that allows the surfaces to slide against one other without friction, and because of this, without damage.

4. Lower extremity joints

4.1 INTRODUCTION TO ANATOMICAL TERMS OF LOCATION IN HUMAN BODY

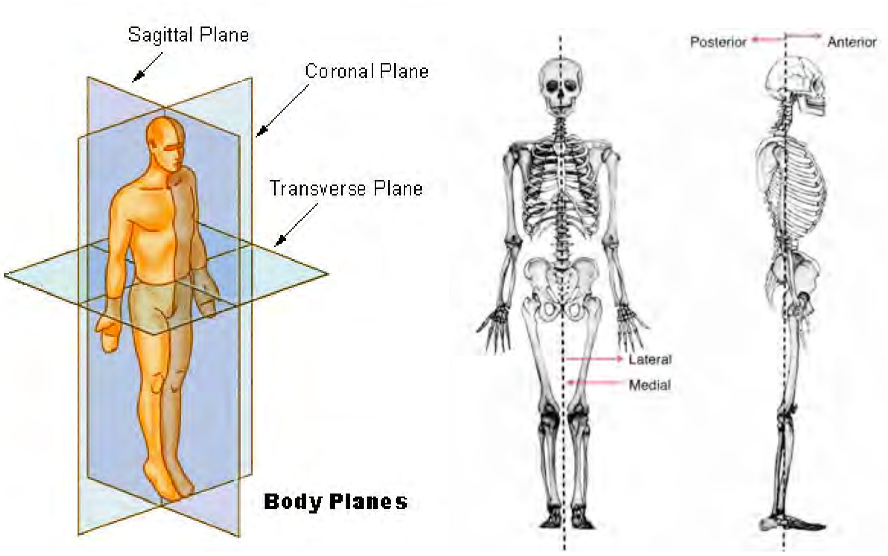

Image 1. Left: main planes in human anatomy. Right: Some anatomical terms of location.

There are three reference planes used in anatomy:

- *Sagittal plane*: divides the body into left and right portions.
- *Coronal (frontal) plane:* divides the body into posterior and anterior portions.
- *Transverse plane:* also cross-section, divides the body into superior and inferior parts.

→ *Lateral and medial*: Lateral refers to parts distant to the sagittal plane, while medial refers to parts close to the sagittal plane. This is used for example in the condyles of the knee.

→ *Anterior and posterior*: Anterior refers to the front of the individual, and posterior refers to the back of the subject, divided by the coronal plane. These terms are found in both the anterior and posterior cruciate ligaments of the knee.

→ *Superior and Inferior*: In humans, superior end refers to the head end, while the feet are referred to the inferior end.

4.2. HIP JOINT

The hip is a synovial joint formed by the head of the femur and the acetabulum, a cup-shaped cavity on the lateral surface of the pelvis. The joint is covered by a tough, flexible protective capsule and reinforced by strong ligaments that stretch across the joint.

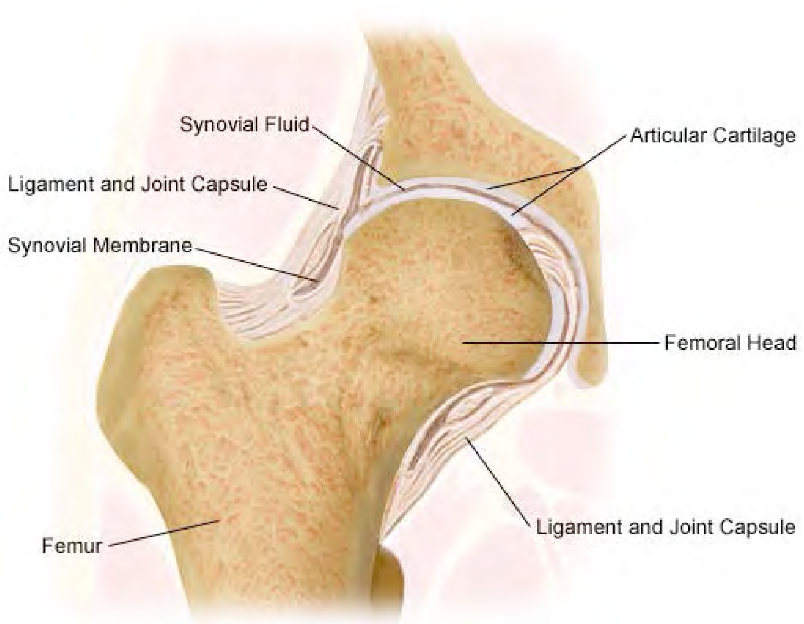

Image 2. Coronal view of the hip joint

Like the shoulder joint, the hip joint is a "ball and socket joint". This means they allow motion in any direction, always with certain limits. This is called circumduction movement (circular movement of a limb such its distal end delineates and arc).

The type of movements described before are possible because the articular surfaces are spherical or semi-spherical, one concave and the other convex, allowing all possible spatial movements (multi-axial joint).

Image 3. Movements of the hip

The thickest part of the femur head is where the transmission of forces takes place, from trunk to low limb or vice versa. The compression lines are where compression forces act when loading the weigh of the body, and the traction lines are where traction forces act (with the adductor muscles of the hip).

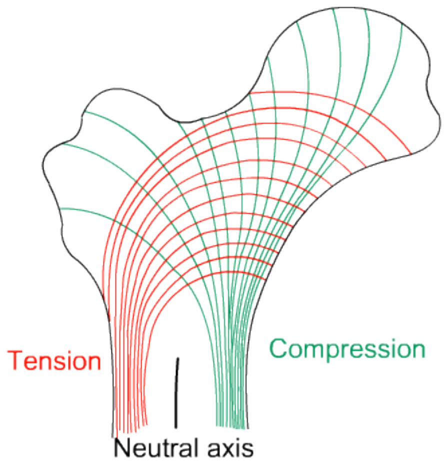

Image 4. Transmission lines of tension and compression and neutral axis in the femur head.

4.3. Ankle Joint

The ankle is the joint where the leg and foot meet. It´s formed by the junction of the tibia and fibula with the talus (or ankle bone). These bones are cushioned by cartilage and connected by a number of ligaments, tendons and muscles that strengthen the joint and enable it to be moved.

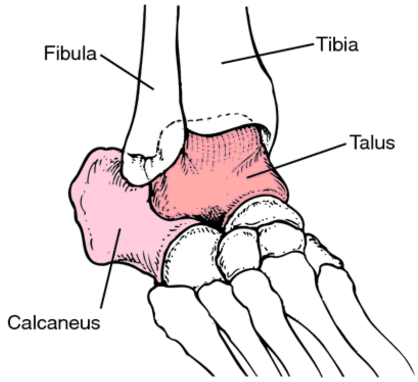

Image 5. Detail of ankle joint

Its function is to transmit the forces of the body weigh and also drives the fine movements of stability.

Since this joint is almost in constant use, it is particularly susceptible to injuries such a sprains and fractures, and also one of the first joints affected by arthritis.

The ankle can perform flexion and extension (dorsiflexion in image 6) in the sagittal plane, abduction and adduction in the transverse plane, and inversion and eversion in the coronal plane.

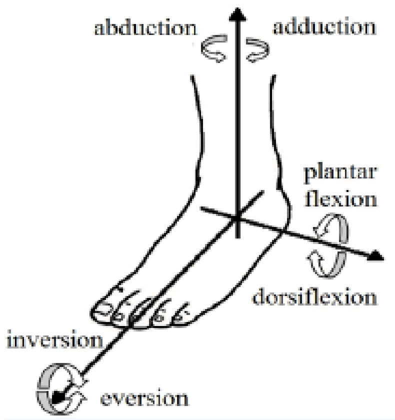

Image 6. Movements of the ankle referred to a three-axes coordinate system.

5. The knee joint

The knee is the intermediate joint of the inferior limb. It is one of the most complex, and the largest joint of the human body. Consists of two articulations: one between the femur and tibia formed by two condyle joints, and other between the femur and patella, where the patella glides through a special groove formed by the two femoral condyles.

The knee has four main ligaments: medial and lateral collateral ligaments (MCL and LCL respectively), and anterior and posterior cruciate ligaments (ACL and PCL respectively).

The fibula is attached to the tibia on its lateral side by a small joint, but never really inners in the knee joint.

The motion of this joint is not simply gliding motion because the articular surfaces of the bones involved are not mutually adapted to each other. It combines rolling at the beginning of the flexion and gliding and the end of the flexion.

Image 7. Sagittal section of knee joint (anatomical draw). Parts in detail.

5.1. PARTS

5.1.1 Bones of the knee

The femur has two femoral condyles that rest on the superior articular surface of the tibia. In the sagittal plane these two condyles are extended backwards, and in the coronal plane they present a groove called patellofemoral groove. Through this groove the patella glides, carrying the forces of the quadriceps muscle to the tibia.

The patella acts as a mechanical leverage, transmitting the weigh of the body in flexion, by gliding on the femur and avoiding wear in the process. It transmits the quadriceps muscle force to the tibia through the patellar ligament, like a pole would do.

The tibia supports the femur. On its superior face the tibia has two condylar surfaces and an intercondylar area, where the cruciate ligaments and the menisci attaches.

5.1.2 Main ligaments of the knee

There are four major ligaments in the knee: two collateral ligaments that prevent excessive displacement of the tibia relative to the coronal plane of the femur, and two cruciate ligaments, that prevent excessive displacement of tibia relative to sagittal plane of femur.

The *lateral collateral ligament* (LCL, also called fibular collateral ligament) goes from the head of the fibula to the lateral face of the femur, stretching obliquely downward and backward. The *medial collateral ligament* (MCL, also called tibial collateral ligament) goes from the medial side of the tibia to the medial face of the femur. These two ligaments prevent excessive movement between femur and tibia in the coronal plane.

The cruciate ligaments of the knee are intracapsular (they are inside the synovial membrane). The *anterior cruciate ligament* (ACL) stretches from the lateral condyle of the femur to the anterior intercondylar area of the tibia. The ACL prevents the tibia from being pushed too far anterior relative to the femur. The *posterior cruciate ligament* (PCL) stretches from medial condyle of femur to the posterior intercondylar area of tibia. The PCL prevents posterior displacement of the tibia relative to the femur.

There are other secondary ligaments in the knee, and splits of the named above; mechanically talking they are not so important.

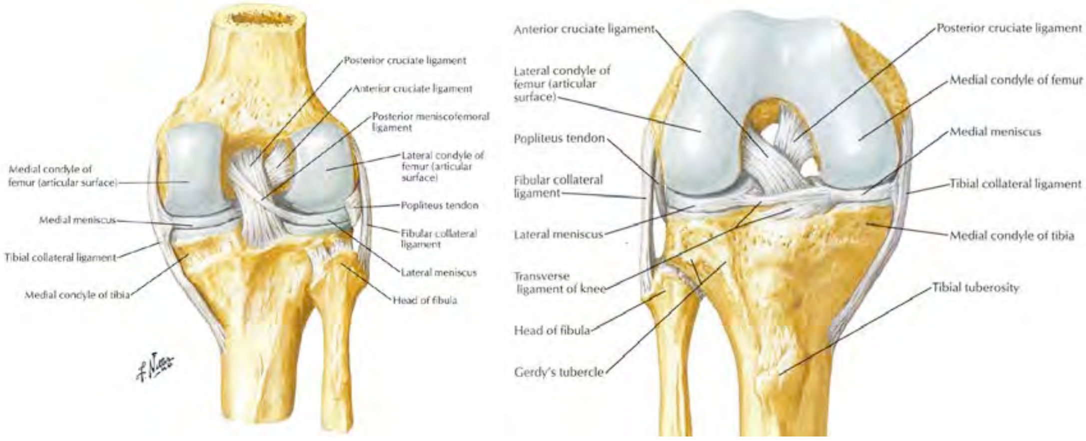

Image 8. Bones and ligaments of knee in detail. Left: knee in flexion, anterior view. Right: knee in extension, posterior view

5.1.3 menisci of the knee

The menisci are two flattened crescent-shaped pieces of cartilage (lateral and medial meniscus) placed in between the articular surfaces (condyles) of femur and tibia.

They are thicker around their outside face and thinner in the inside, creating a perfect interface, extending the contact condyle surface in touch. Because of this, the menisci act as shock absorbers and increase the knee stability.

They also help to protect the condyle surfaces of both femur and tibia from rubbing each other with excessive wear.

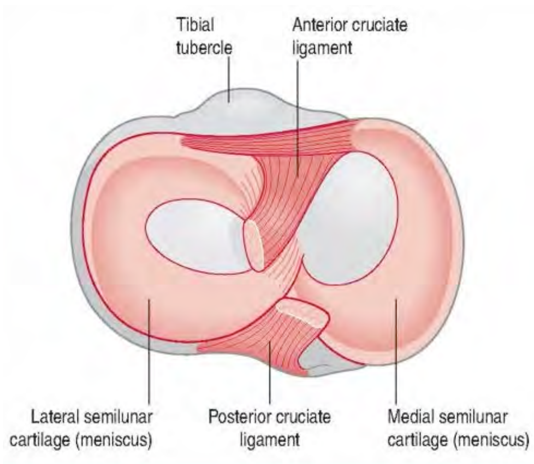

Image 9. Representation of knee menisci. Both lateral and media menisci are attached to the intercondylar area of the tibial plate.

5.2. MOVEMENTS

When talking about movements of the knee, it is referred to the relative movement between femur and tibia, this is, the relative movement between the upper part of the limb and the lower part.

The knee can perform movements within six degrees of freedom:

1. Flexion/extension in the sagittal plane
   This movement involves rotation and gliding of femur along the knee. The flexion is about 140°, and the extension 0°.

2. Displacements in the coronal plane (varus/valgus)
   These movements are only possible when the knee is slightly in flexion. Varus is the displacement of the tibia lateral relative to the femur (inward of the center of the body), while valgus is displacement of the tibia medial relative to the femur (outward of the center of the body).

3. Displacements in the sagittal plane (anterior/posterior, proximal/distal movements)
   These movements depend on the flexibility of the knee, the compression it has and the force used to do the translation. The anterior translation can vary from 2 to 10 mm, and the posterior from 0 to 6 mm.

4. Displacements in the transverse plane (internal/external rotation, medial/lateral movements)
   As before these movements are only possible when the knee is in flexion.

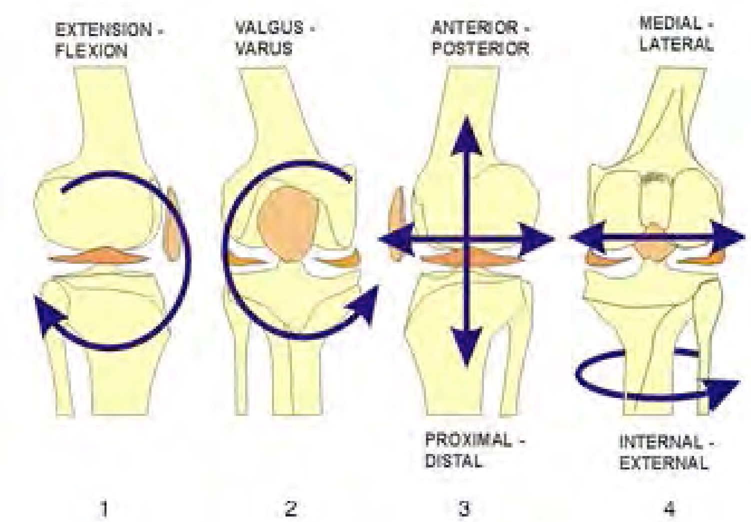

Image 10. Movements of knee. 1: Flexion/extension in sagittal plane. 2: Displacements in coronal plane. 3: Displacements in sagittal plane. 4: Displacements in transverse plane

5.3 MODELS OF THE KNEE

A large number of patterns have been established, but neither of them has reached the right articular movement. Three of them are presented:

- Hinge model

The rotation is done around one fixed axis. This rotation is the flexion of the knee. Based in only two planes. One DOF.

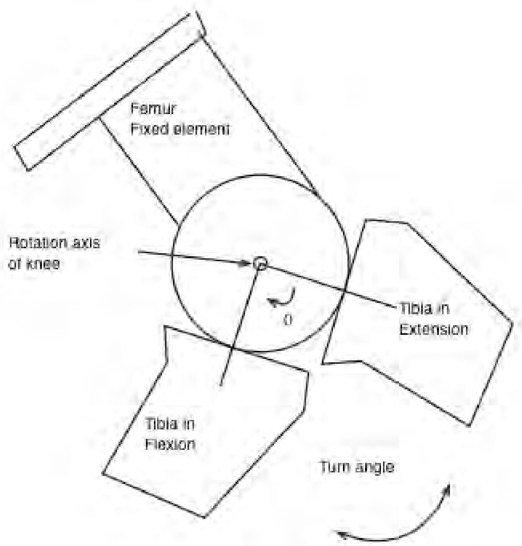

Image 11. Hinge model

- Planar model

The model allows movements of rotation (flexion/extension) and anterior/ posterior and proximal/distal displacement. Two DOF

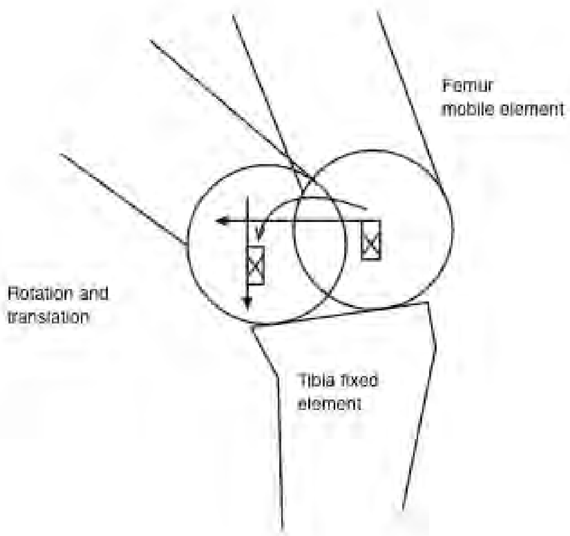

Image 12. Planar model

- Four-bar linkage model

This model considers the cruciate ligaments as two crossed bars, this way the femur and tibia are another two bars, forming a four-bar mechanism. It considers flexion/extension in sagittal plane and rolling of femur on tibia. Two DOF.

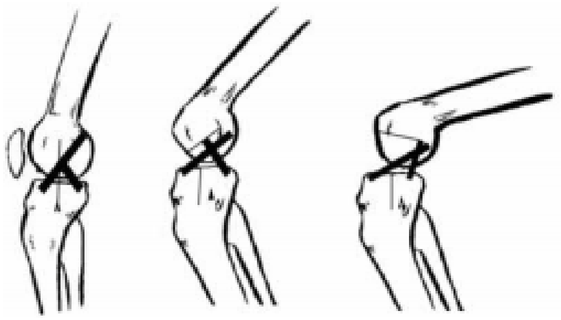

Image 13. Four- bar linkage model

5.4 THE PATELLA

The patella is the connection between the quadriceps femoris muscle (by the patellar tendon) and the tibia (by the patellar ligament). When it moves relative to the femur, it does gliding through the anterior femoral condyles, which prevent lateral dislocation during flexion.

The patella also gives mechanical advantage to the extensor muscles by increasing the lever arm of the extension mechanism from the axis of flexion/extension.

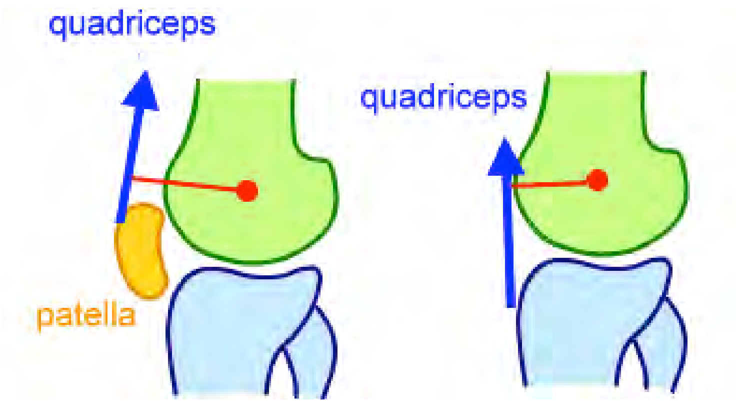

Image 14. Larger lever arm that the patella provide.

When the knee is in flexion, in the sagittal plane, the forces of quadriceps and patellar ligament are in closer angle, both acting on the patella. The resulting force is called patellar compression force (PCF). It increases with the knee flexion.

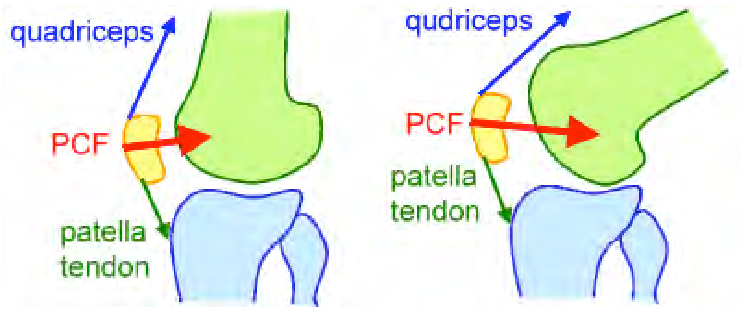

Image 15. PCF as vectorial sum of the quadriceps force and the patellar tendon force

In the coronal plane, the quadriceps pulls from the patella with certain Q angle (quadriceps angle) that is formed between the pull direction of quadriceps and the line on the patellar tendon. This deviation is counteracted by the femoral condyles.

6. Knee Modeling From DICOM Data

6.1 Modeling process

- Image acquisition:

For this project an MRI was obtained from a healthy knee, courtesy of Javier Arnaiz, radiologist in Valdecilla hospital (Santander, Spain).

After trying to obtain the bones' models, it was noticed that for hard tissue like the bones have, and MRI has not the appropriate contrast, which is in fact better than in a CT scan. Because of this reason, the bones and the surrounding tissues like cartilage, ligaments and tendons have very closed gray scale, although visually parts are very distinguishable.

Then a CT-scan was obtained, from "Visible Human Project CT Databases" University of Iowa (https://mri.radiology.uiowa.edu/visible_human_datasets.html). The CT-scan of the knee has high contrast between high dense tissue from bones and soft tissue (the rest). This is why it is good for modeling the bones but not so good when modeling ligaments or tendons.

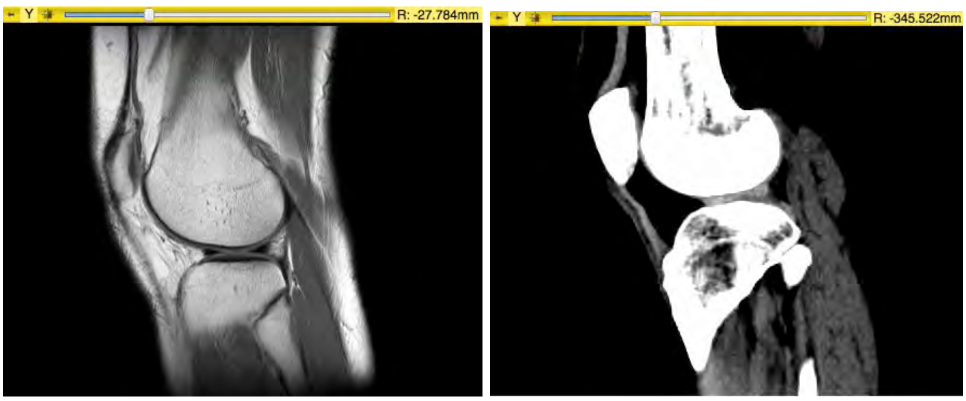

Image 16. Comparison between MRI (left) and CT-scan (right).

- Model building

The program used to obtain the models of the various parts of the knee was 3D slicer (http://www.slicer.org/) preferred to the other program tried Osirix (http://www.osirix-viewer.com/). The selection of the first was conditioned by the material learning-related to this program available on the Internet that allowed a quick learning of the process for obtaining an ".stl" file model. But it has also the advantage of Visualization of DICOM files and label maps at the same time that a 3D representation of the models.

- Post-processing

Once all the models of the parts required are obtained, the .stl need to be imported by a 3D CAD program. The chosen was Solidworks (http://www.solidworks.es/). It is capable to import .stl files as surface or solid, but the complexity of the raw .stl file required too much memory, making the program unstable and eventually, crushed.

Another solution Solidworks offers is to import the .stl file as mesh file. For this, the complement "Scanto3D" to must be activated.

6.2 DICOM STANDARD FOR MEDICAL IMAGES

DICOM are the initials for Digital Imaging Communications in Medicine. It is the international standard for medical images and related information (ISO 12052). It defines the formats for medical images that can be exchanged for clinical use, and also a network communications protocol. DICOM is implemented in almost every radiology, cardiology imaging, and radiotherapy device (X-ray, CT scan, MRI, ultrasound, etc.)

Since its first publication in 1993, it revolutionized the practice of radiology replacing X-ray film with digital workflow, widely adopted by hospitals, even doctor' and dentist' offices.

There is several DICOM image processing software, from simple freeware viewers and software package for image processing dedicated to DICOM (Osirix, 3D slicer) to highly specialized image processing and analyzing software used by medical and engineering companies (Mimics® Innovation Suite by Materialise HQ).

The way the medical images usually take place is the tomography, which refers to the extraction of images by sections, using any type of penetrating wave as X-rays for CT-scan, radio-frequency waves for MRI, etc.

6.3 GETTING AN .STL FILE FROM DICOM DATA WITH 3D SLICER PROGRAM

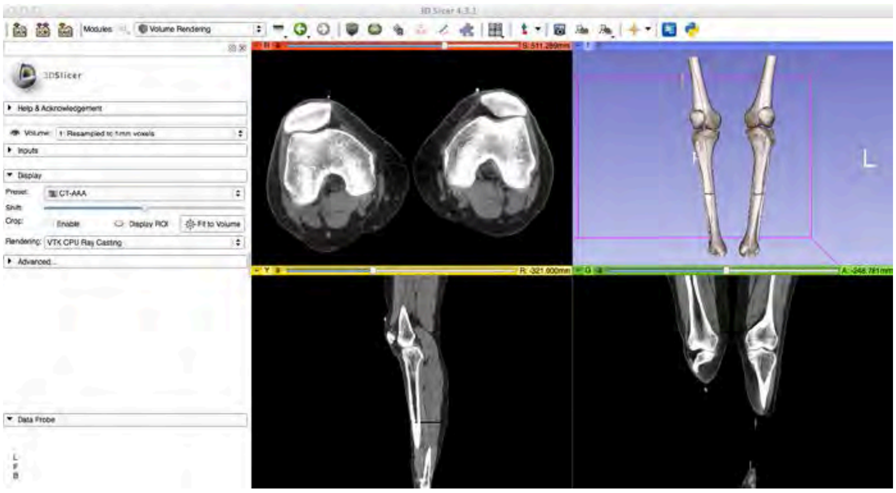

Image 17. General interface window of 3D slicer. Red: Transverse plane. Yellow: Sagittal plane. Green: Coronal plane. Blue box: 3D representation of models.

The DICOM file used contained the CT-Scan of both female legs, but the region needed was only the right knee. To solve this the program counts with a crop volume tool, with which we can select the exact volume we want to work with.

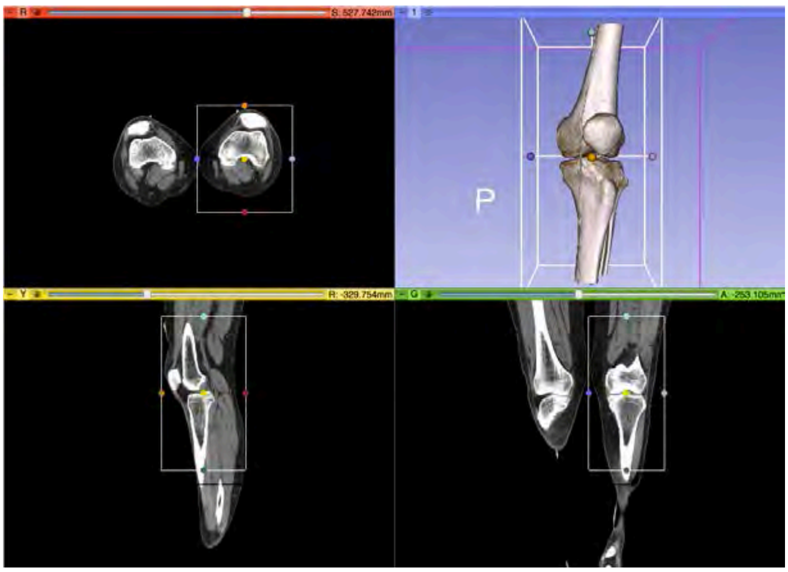

Image 18. Crop volume tool. Selecting the left knee as region of interest.

After defining the working volume, we use the model editor of the program to create a label map of the model. This is, a pixelated image put on top of the DICOM image, for each slide that the body we are modeling is in. There are few tools the program has to achieve this with: First a Threshold effect tool that allows to select a range of gray color. This is very useful with the bones since they have distinctive contrast between white and the gray surroundings.

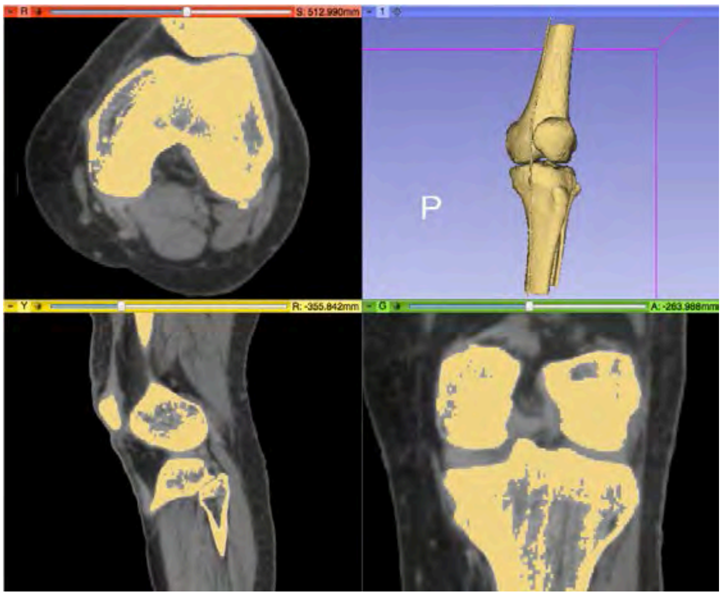

Image 19. First rough selection of label map for the knee bones.

Other parts, as ligament parts, blood vessels or nerves may have that same white tone. Other tools are for erasing undesirable parts, or paint others that should have been painted. By using these tools we improve the model filling holes that may appear or remove parts that are not from the model.

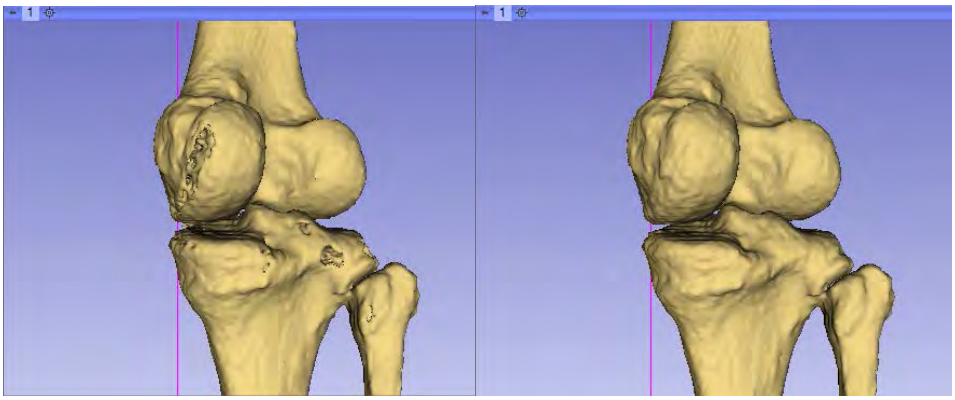

Image 20. Improvement in the bones model by using the label map edition tools.

The same can be done for ligaments, tendons, etc. All models can be exported then as ".stl" files.

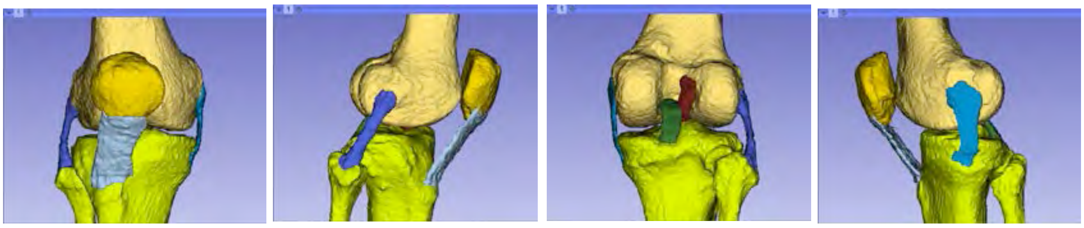

Image 21. Final models in .stl file. Femur (light yellow), Tibia+Fibula (light green), Patella (yellow), ACL and PCL (red and dark green respectively), LCL and MCL (Dark blue and blue respectively), Patellar ligament (light blue).

Image 22. Final model. Isometric view

6.4 IMPORTING AN .STL FILE WITH SOLIDWORKS

Once we have activated the "Scanto3D" complement, we can directly open an .stl file as mesh file. The mesh is a complex composition of thousands of triangles. The complement mentioned enables tools to simplify the mesh, smooth its surface, and leave it ready to convert to solid. After this another tool is used to convert it to solid (the actuation lines can be automatically created, in black, or hand created, in orange)

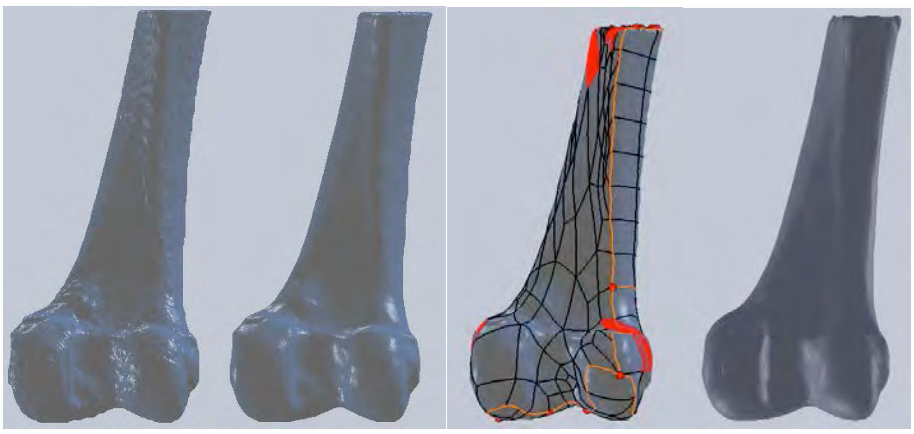

Image 23. Process to improve a mesh and make a solid part out of it. From left to right: raw mesh, smooth mesh, Solid part with actuation lines, final solid part.

6.5 SIMULATION OF KNEE FLEXION MOVEMENT WITH SOLIDWORKS

Once all the solid models are obtained, an assembly can be performed with Solidworks. When the movement constraints are placed, the next and final step is to perform the movement simulation.

The videos obtained simulate:

- Fixed femur and free tibia in flexion around it. May simulate the flexion while standing up.
- Fixed tibia and free femur in flexion around it. May simulate a person sitting down and standing up.

Various attends to create the model were failed. The first idea was to make each condyles glide separately; by creating two splines that follow the femur condyles' shapes, and planes on the tibia plate. But the movement restrictions that Solidworks allows with splines are limited (just a single point to follow the spline curve).

The solution proposed is a kinetic model where femur, tibia and patella share a parallel plane in all the movement. The patella glides through a spline that has the shape of the intercondylar groove, and is attached to the tibia by a rod that emulates the patellar ligament. The femur rolls and glides on the plane of the tibial plate, by means of a circumference adjusted to one of the condyles.

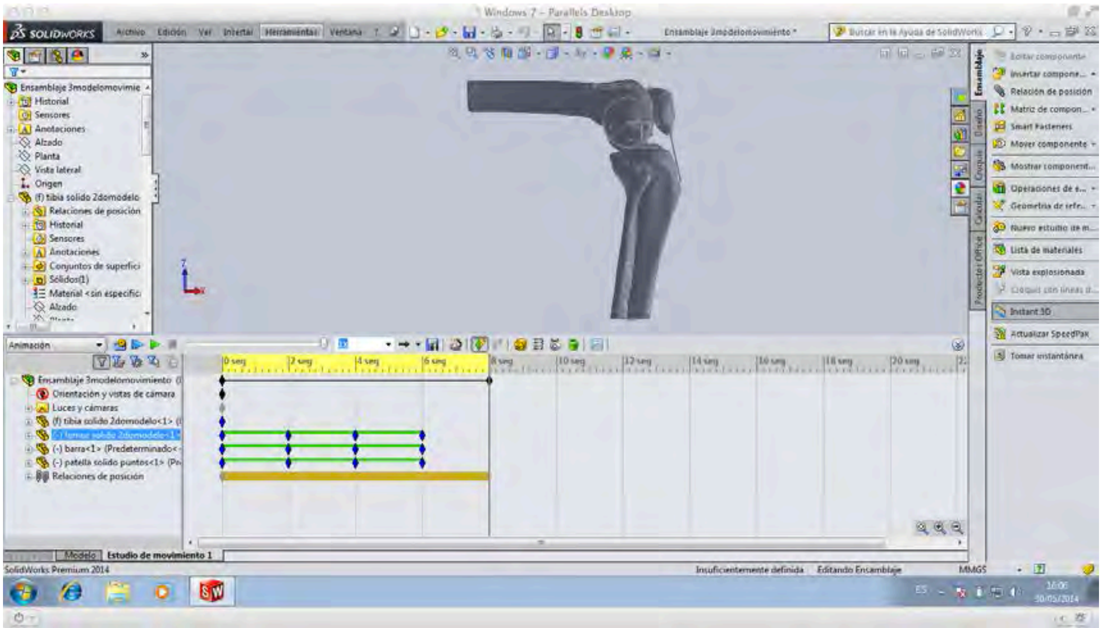

Image 24. Solidworks movement-study interface.

7. Results

- Eight ".stl" files were obtained of eight main structural components of the knee:

  - Femur
  - Tibia
  - Patella /Fibula
  - Medial and lateral collateral ligaments (MCL, LCL)
  - Anterior and posterior cruciate ligaments (ACL, PCL)
  - Patellar ligament

- Four Solidworks Part Documents (.SLDPRT) from the .stl models of femur tibia and patella as solid parts with sketches for assembly. The fourth document is the rod that emulates the patellar ligament.

- Solidworks Assembly Document (.SLDASM) with the parts put together and the movement study.

- Videos:

  - .avi file with femur fixed (flexion while being stand up)
  - .avi file with tibia fixed (sting down and standing up)

8. Conclusions

The structure of the human knee is very complex, with a movement that involves rolling and gliding between femur and tibia, and gliding of the patella along the intercondylar groove of femur, with almost constant distance to the tibia. This makes it particularly difficult to simulate the real movement between these three parts.

Classic CAD programs such Solidworks, Autodesk inventor, Catia, are made for engineering parts, understanding this as parts with flat, cylindrical, spherical, spline defined surfaces, this is, some short of mathematical surface, or objects with some symmetry in planes or axes. The human body has a plane of symmetry, but besides this, it has complex surfaces and structures in all its integrity, making very difficult its study with these programs made for operations as extrusion, revolution, etc. Nevertheless, they usually incorporate special complements for this type of work.

The presented model is an approximation of the real flexion movement of a knee. Some improvements that can be performed are:

- Give the rod between femur and tibia elastic consistency, emulating this way the elasticity of the patellar ligament.
- Make flexible models for the ligaments. These are flexible tissues that for became part of the model they need to be attached in their extremes to bones, being able to bend after the junction, and being able to stretch.
- A more realistic movement would be obtained by having the condyles gliding separately.
- When obtaining the solid part in Solidworks, create straight actuation lines on condyles to after use them as rails for the movement.

This work is realized from mechanical engineering point of view, so it needs a mechanical engineer or related for revision. But since it is medical- related, it also needs a revision from a medicine expert to have any validation.

The technique of obtain a 3D model can be applied for non-medical models too, as a tool for reverse engineering. With a 3D scanner a mesh or point cloud is obtained out of any piece. With the process used in this work that mesh can be imported in a CAD program like Solidworks and be modified and improved in terms of design.

9. Literature

9.1. Books

Atlas of Human Anatomy by Frank H. Netter Published June 23rd 2006 by W.B. Saunders Company (first published 1989). English

Anatomy of the Living Human: Atlas of Medical Imaging. Konemann UK Ltd (24 de mayo de 2009). English

9.2. Literature on the Internet

http://medical-dictionary.thefreedictionary.com/

http://medical-dictionary.thefreedictionary.com/ligament

http://medical-dictionary.thefreedictionary.com/tendon

http://upload.wikimedia.org/wikipedia/commons/3/34/BodyPlanes.jpg

http://www.culturismo.cl/wp-content/uploads/2012/04/vista-esqueleto-humano.jpg

http://www.childrenshospital.org/~/media/Centers%20and%20Services/Programs/A_E/Child%20and%20Adult%20Hip%20Preservation%20Program/Hip.ashx

http://wikiskeleton.wikispaces.com/file/view/ball_ans_socket.jpg/325650784/101x119/ball_ans_socket.jpg

http://www.doitpoms.ac.uk/tlplib/bones/structure.php

http://www.scielo.org.co/img/revistas/dyna/v79n176/v79n176a06fig04.gif

http://img.tfd.com/elsevier/u13-01-9780443102158.jpg

http://www.jointinjury.com/knee/images/knee1a.gif

http://medical.nema.org/Dicom/about-DICOM.html

http://www.fundacionmapfre.org/fundacion/es_es/images/vol03-n3-art7-biomecanica-rodilla_tcm164-5158.PDF

http://www.pt.ntu.edu.tw/hmchai/Kinesiology/KINlower/Knee.htm

http://medical-dictionary.thefreedictionary.com/_/viewer.aspx?path=elsevier&name=u13-01-9780443102158.jpg