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Application Specific Adaption of a Numerical Based Surgical Process

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Abstract

Postoperative pain and functional limitations after an Anterior Cruciate Ligament reconstruction is usually inaccurate placement of the femoral and tibial tunnel. This paper presents a technology workflow including a software pipeline for patient-specific preoperative planning and analysis of the knee joint including functional-mechanical properties.

1 Introduction

The reason for postoperative pain and functional limitations after an Anterior Cruciate Ligament (ACL) reconstruction is usually inaccurate placement of the femoral and tibial tunnel. Between 10-15% of these interventions are not satisfying whereas tunnel positioning is crucial for the success of this intervention (Leroux T, 2014).

Patient-specific 3D simulations allow more accurate, economical and efficient interventions in such orthopaedic surgeries. The Finite Element Method (FEM) is a common computational method for this application. Patient-specific FEM based on medical images has great potential to aid in clinical decision making, designing implants, planning surgeries and monitoring outcomes (Neak ML, 2010).

As conventional surgery planning is realized using rigid body analysis considering bone structures only, the interaction of soft tissues is missing and thereby the functional behaviour of the anatomical joint is not considered.

We develop a semi-automated technology workflow including a software pipeline for patient-specific preoperative planning and analysis of the knee joint including functional-mechanical properties.

[*] Masterminded and created the final version of this document

2 Materials and Methods

A high resolution MRI dataset (0.3x0.3x0.3 mm) from a human cadaver knee was used to build a reference FE model comprised of bones, cartilage, menisci and ligaments (Ansys v16, Canonsburg, PA, USA). Material properties were chosen from the literature (E. Peña, 2007) and boundary conditions were defined to simulate several clinical tests, e.g. Lachman test to investigate the stability of the anterior cruciate ligament and pure flexion to 90°.

Subsequently, a coronal and axial MRI dataset (0.3x0.3x3.6 mm) with clinical protocols was acquired, fused and registered to the reference MRI image using landmark-based rigid initialization followed by intensity-based multi-resolution b-spline deformable registration (Klein S, 2010). Resulting 3D deformation fields were used to deform the geometry of the reference model to obtain a patient-specific FE model (Figure 1). The deformation fields were applied to the reference model in SpaceClaim Design Modeler v16.1 with Application Programming Interface (API). Through a programmed extension with API it is possible to virtually operate and attach implants. By completing the geometrical part, it is possible to transfer the model to Ansys v16 including all boundary conditions.

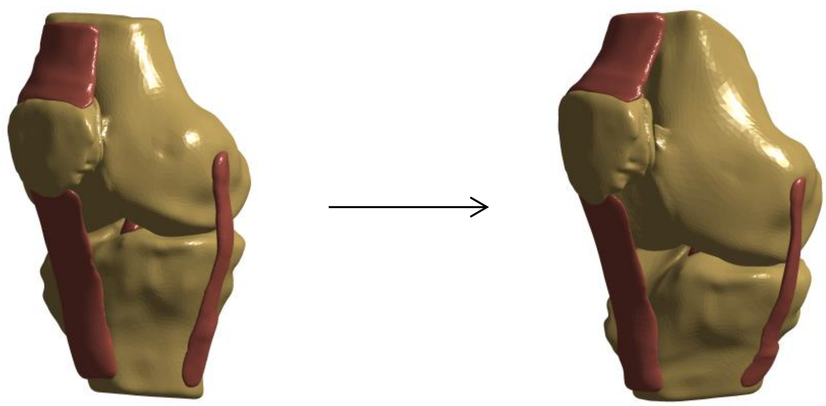

Figure 1: Finite Element Knee Model; Reference Model (left), Patient-Specific Model (right)

3 Results

It is possible to obtain a patient-specific FE model from a clinical MRI dataset including all boundary conditions in less than 19 minutes on two cores with 3.5 GHz using the morphing process.

Depending on the defined clinical simulation, solving the mechanical system is more time consuming and takes at least two hours on two cores with 3.5 GHz for a Lachman-test. The subsequent meshing of the patient-specific geometry leads to a high quality mesh and a stable finite element simulation. The biomechanically correct placement/alignment of components for an ACL surgery is possible within a virtual environment.

This workflow allows preoperative planning, analysis of acting forces and simulating the stability of the knee joint for an improved ACL surgery (Figure 2).

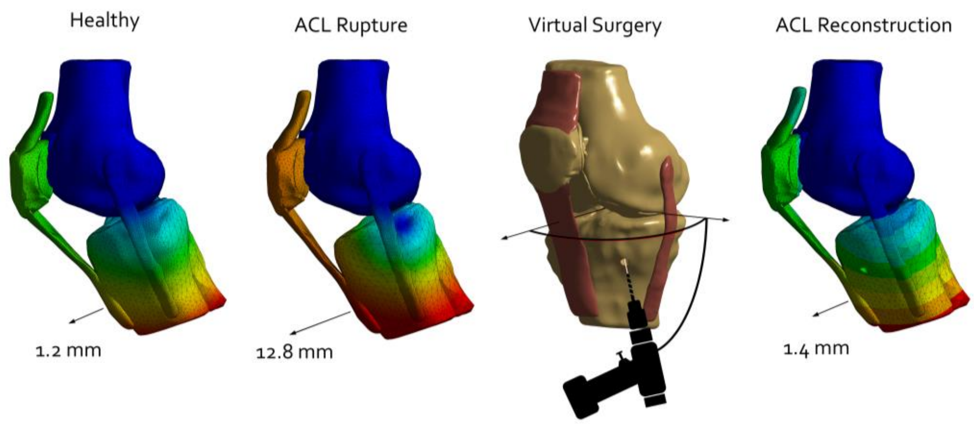

Figure 2: Range of Motion Analysis – Virtual ACL Reconstruction with a Patient-Specific Finite Element Knee Model

4 Discussion

The results indicate a stable workflow for functional simulations of a patient-specific knee using Finite-Element-Analysis with a further option to virtually operate. This method is used to achieve a patient-specific geometry before meshing, which results in a stable FE simulation. As shown in (Pauchard Y, 2015), deforming the mesh to obtain a patient-specific model leads to divergence during FE solving. The huge amount of data in such a calculation leads to an impossibility to use it intraoperatively at the moment. Preoperative analysis of acting forces, stresses and strains is possible. The biomechanically correct alignment and implantation of components can be determined and crucial, patient-specific information regarding the resulting range of motion is obtained. This method supports the accurate placement of the femoral and tibial tunnel for an ACL surgery which reduces the risk of graft failure or unsatisfactory results and might reduce long-term degeneration observed after reconstruction (Maria K. Kaseta, 2008). Thus, this method leads to improve a patient-specific solution in orthopedic surgeries and serves as a virtual second opinion although it requires a clinical confirmation to quantify the benefits.

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