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Challenges in modeling total knee arthroplasty and total hip replacement

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Abstract

Total knee arthroplasty and hip replacement are commonly used procedures in which an ailing knee or hip joint is replaced with a carefully engineered artificial joint. Multibody models of healthy knee and hip joints are used extensively to design artificial knee and joints. The quality of the replacement joint is thus intrinsically related to the quality of the multibody models. In this work, the quality of a kinematic knee model is assessed by comparing predicted knee kinematics to cadaveric knee kinematics under several patellar overstuffing conditions. In addition, the micro motion at the hip joint (between the femoral head and the acetabulum) under varying loads is experimentally measured using a cemented and a cementless cadaveric hip joint.

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1. Introduction

The knee and the hip are the two most common joints that are most likely to be replaced during our lifetime due to wear and tear of cartilage, bone degeneration and other factors where weight bearing is a factor. Additional pathologies such as arthritis, infection and injuries are also reasons for having a total knee arthroplasty. The benefits of a TKA (Total Knee Arthroplasty) and THR (Total Hip Replacement) stem from the fundamental understanding of the knee and hip mechanics and the design, and material advancement that has evolved for the past 20 years. To increase longevity, functionality, and natural dynamics of the knee or hip we need to identify the modalities and current issues associated with the surgical procedures, implant design, implant/bone interface in building realistic models in MBDS. In most cases, the preparation for building the model relies a great deal on model assumptions that involve many geometric simplifications and input of material properties, some of which are poorly understood. Therefore, it is essential to develop methodologies to validate model predictions to build confidence in the model before exploration of potential applications. In this paper a TKA knee model as well as THR model are presented followed with experimental data used to validate the kinematics and stress-strain interfaces. The models will address

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the implant fixation methodology like cemented, cementless and pres fit methods. The current knee and hip models use a combination of medical imaging methods (computed tomography and magnetic resonance tomography), CAD (Computer Aided Design) and MBDS (Multi-Body Dynamics System), as well as ANSYS. This approach is ideal in the design of a modular knee.

2. Total Knee Arthroplasty

2.1. The Knee Anatomy and TKA

The knee is a joint bearing and one of the most complex dynamic articulations in the musculoskeletal system. Three bones compose the articulation: tibia, femur and patella, which are surrounded by a structure of tendons and ligaments whose main function is to provide stability and functionality (Fig. 1). Being a diarthrosis the motion of this particular joint is strongly dependent on the shape of the articular cartilages and condyles covering the tibia and the femur surfaces. The patella extended function can be described by a pulley system that tries to keep the patella within the groove of the femoral component during knee flexion-extension [1].

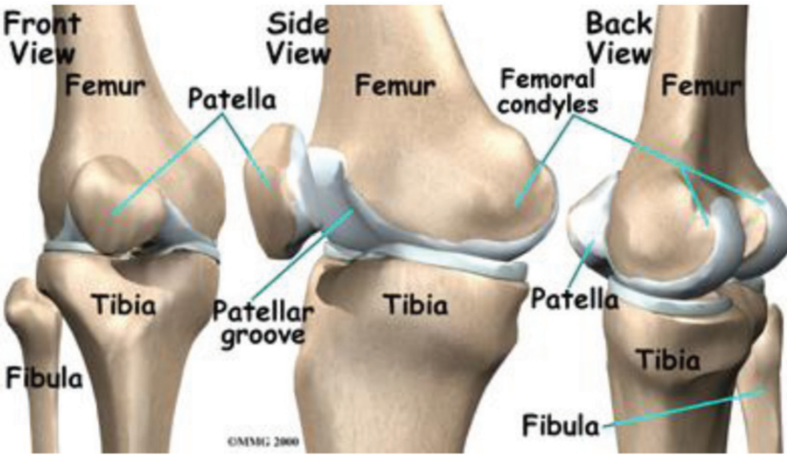

Fig. 1: Anatomy of the knee (As shown by Medical Multimedia Group)

In the study of total knee repair, wear of the cartilage in most cases induces arthritis, pain and cause destabilization of the knee which result into TKA. The latter usually limits the knee progression disease and improves the quality of life for the patients. The success of the TKA depend great deal on the balancing of the knee after the following steps are performed: 1) proper measurements and removal of the cartilaginous elements followed by the selection of the tibia tray and insert 2) resurfacing of the patella femoral components and selection of a design conforming to the patient knee geometry (see Fig. 2) [2].

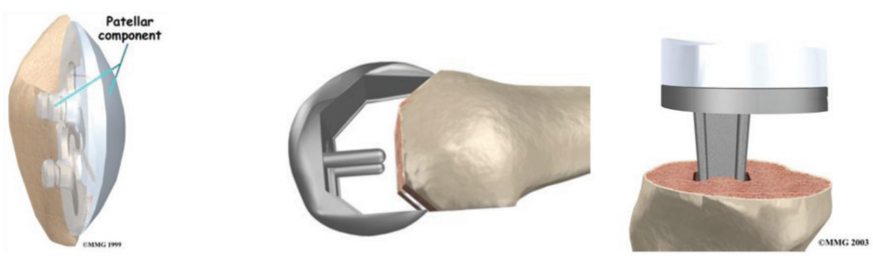

Fig. 2: Basic steps in TKA: patella, femur and tibia resurfacing. (As shown by Medical Multimedia Group)

2.2. Experimental Analysis of Knee Kinematics after TKA

The purpose of the experiment was to evaluate the knee kinematics during TKA and in particular try to assess the flexion-extension relation to insert thickness and patella overstuffing (increment of patella thickness). We have examined several patellar configurations for six fresh knee frozen cadavers (Fig. 3). For each configuration, the overstuffing varied from 0-8mm by an increment of 2mm. The Optrack system [3] was used to measure the knee tilt angle θ_y (angle of rotation around the y-axis) and the patello-femoral flexion angle θ_x (angle of rotation around the x-axis) (Fig. 4). As shown in Fig. 5 the flexion angle θ_x is not influenced by the overstuffing, however the overstuffing when larger than 4 mm the tilt angle increase in amplitude. This provides an insight into some of the clinical claims that overstuffing during TKA does not affect the sagittal plane motion but causes instability and tilt if the medial and lateral rotation suggesting possible instability and dislocation of the patella.

Fig. 3: Optrak apparatus

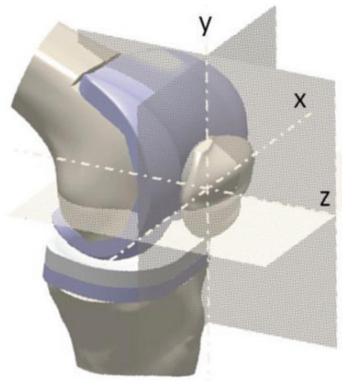

Fig. 4: Reference system adopted

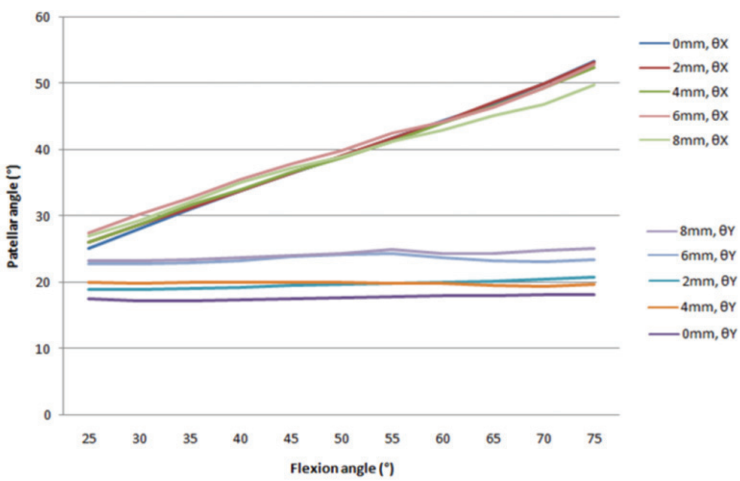

Fig. 5: Patella tracking during flexion

2.3. FEM Model Development

The modeling of the knee requires some intricate details and constraints that are directly related to the actual methodology being used in surgery, the selection and implementation of the different hardwares and finally the evaluation and estimation of the tendon forces. The initial model being built is based on data from the Visible Human Data Set supplied by the US National Library of Medicine, the prosthetic implants were digitized and modeled based on data extracted from Depuy Johnson and Johnson website using commercial image processing software (Simpleware©Scan Ip) and CAD (CATIA V5©).

The characterization of the tendons required additional tests to extract the stress strains function relations, which included both the tibia tendons as well as those of the quadriceps muscles. The knee structure plays a crucial role in the kinematics and dynamics of the knee and the available literature data was insufficient to model the soft tissues and muscles. Figure 6 shows some of the basic tests we performed following the Mooney-Rivlin model [4].

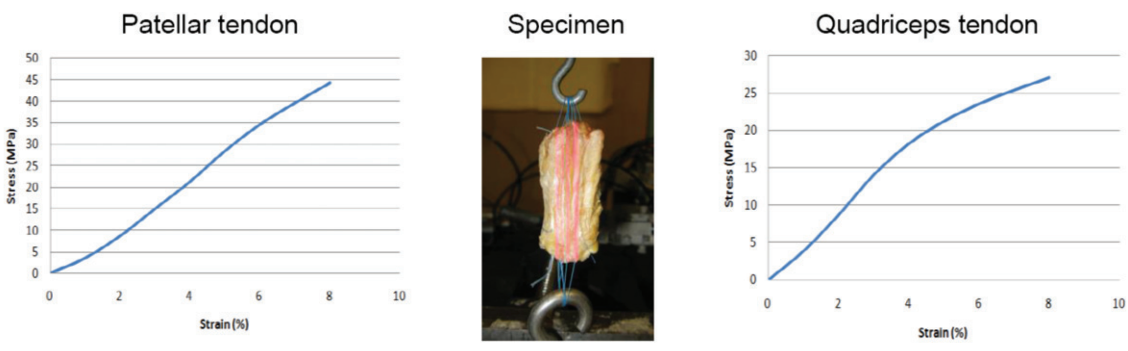

Fig. 6: Experimental data for mechanical characterization

The FEM model developed in ANSYS Workbench©has been validated using the experimental data previously described in our experiment and was used further to understand the stress distribution in the tendons with different patella's prosthesis keeping the same total patellar thickness [3]. Figure 7, shows the volume removed from the patella for the resurfacing, as amplitude of the resurfacing we have assumed the distance between the 'reference plane' (plane, containing the extreme posterior point of the patella evaluated in the perpendicular direction of the coronal plane, z axis, and parallel to the coronal plane, plane xy, Fig. 4) and the cutting plane (assumed parallel to the reference plane).

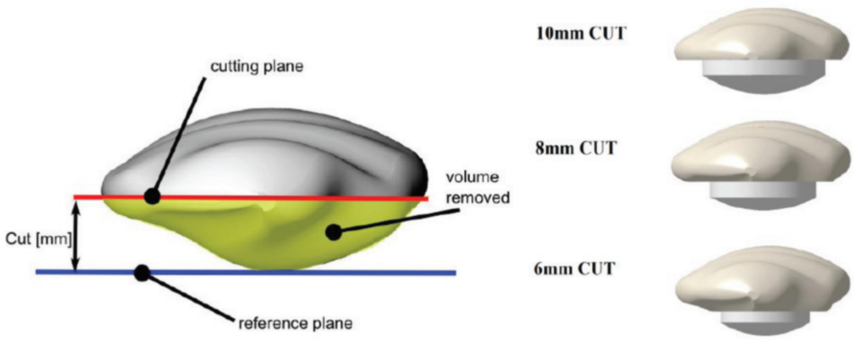

Fig. 7: Description of patella resurfacing and the corresponding button

In addition to the patella tracking during flexion extension contact and stress analysis of the patella with the femoral component were performed for different button thicknesses. Figures 8 and 9 show the results of maximum stress at different flexion angle. One can easily see how the stress is higher for the 6*mm* thickness and in particular at 30°. This was a limiting factor for the Optrack in terms of getting full extension data.

3. Total Hip Replacement

3.1. The Hip

The hip, similarly to the shoulder, represent the joint of the human body with major degrees of freedom allowing rotation around an indefinite number of axis. The complexity of this articulation and the amplitude of the loads

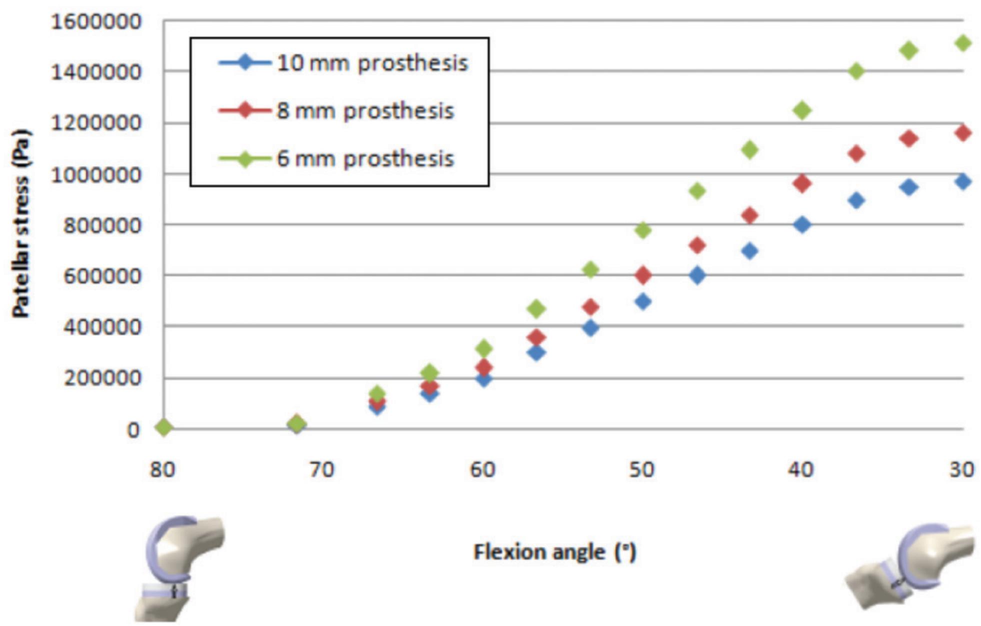

Fig. 8: Results in terms of stress for each configuration (flexion angle is the angle between femur and tibia during the flexion movement)

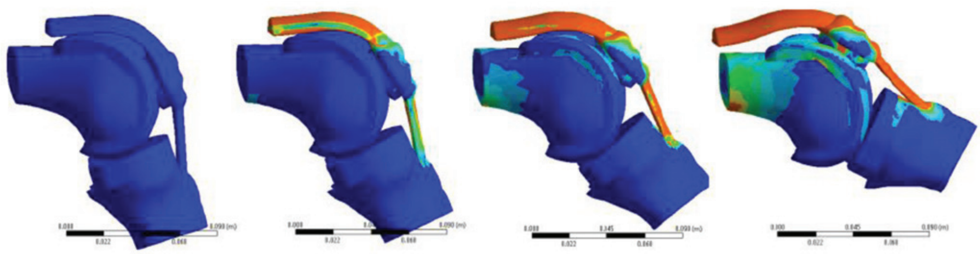

Fig. 9: Stress distribution during the movement with evidence of the sliding of the patella along the trochlear groove for the cut of 8 mm

supported, make of it an important element of clinical interest. The articulation is an enarthrosis, composed by a ball (head of femur) and a socket joint (acetabulum, Fig. 11).

The wear of the cartilaginous layers cause pain symptoms and muscle contractions with consequential limitation in mobility of the articulation. The total hip replacement, is the technique used to solve this problem in severe cases. The actual technique, still uses the method developed by John Charnley in 1960s [5], is based on the resection of the femural head and of the acetabulum and the replacement with prosthesis (Fig. 11) in origin, anchored with acrylic bone cement [6].

To build on the challenges of both knee and hip joint, our objective in THA was to assess the micromotion at the cup/bone interface and provide some measure and understanding of the understanding of the behavior of the cup, in terms of the micromotion.

3.2. Experimental Data

Fresh cadavers were used to assess the dynamic loading effects on a cup/bone interface in the presence of bone defect and cement repair. An apparatus of sensors and fixtures was designed and using an instron machine varies loads were tested. A set of 9 LVDT sensors with a tolerance of 5 microns were used and displacements were measured with

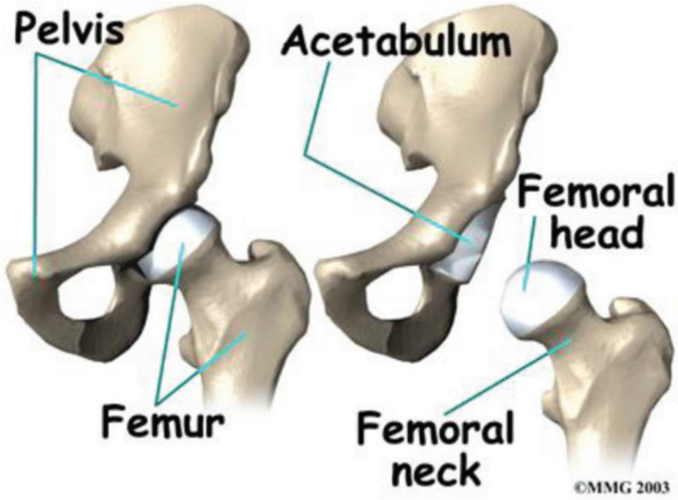

Fig. 10: Anatomical images of the Hip (As shown by Medical Multimedia Group)

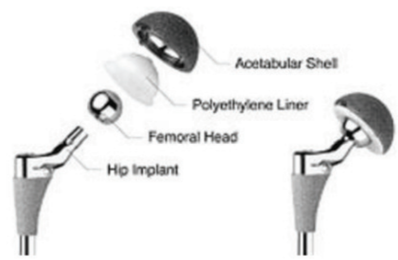

Fig. 11: Example of prosthesis used for THR (courtesy of Zimmer Inc.)

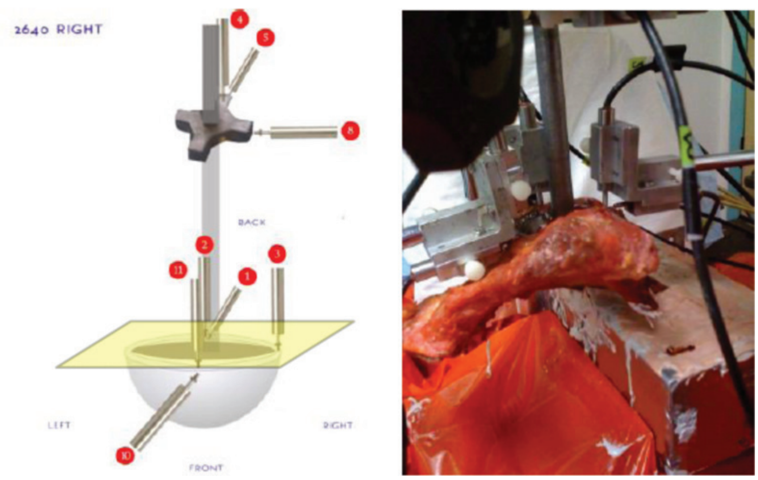

Fig. 12: Experiment setup and layout for the LVDT sensors

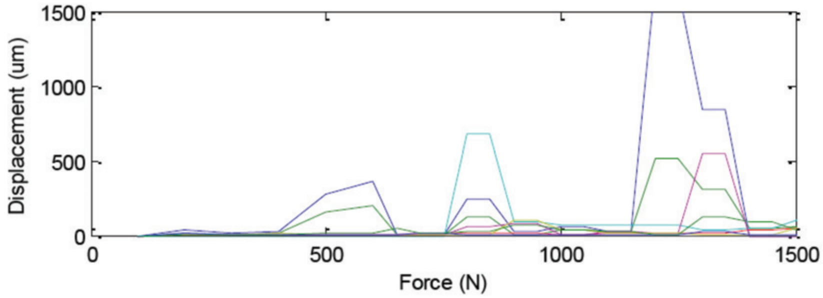

Fig. 13: Cementless specimen displacement

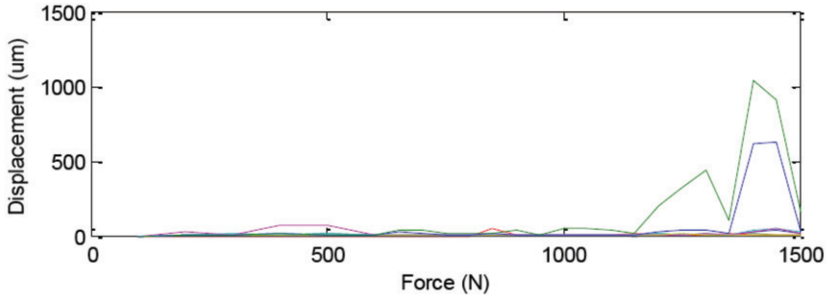

Fig. 14: Cemented specimen displacement

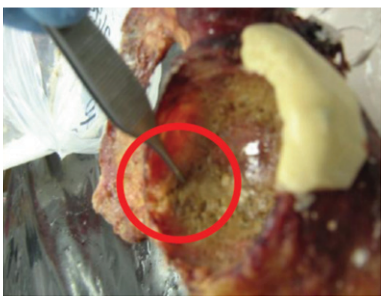

Fig. 15: Cemented acetabulum after removal of cup

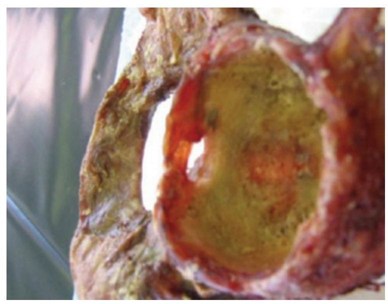

Fig. 16: Cementless specimen after cup removal

load values varying from 100 N up to 1500 N with increments of 100 N. The force direction was set perpendicular to the plane of the cup and a moment was added using a moment arm of 6 mm in opposite direction to the spine of ischium (Fig. 12).

For loads less than 1300 N it seems that the micromotion/displacement is quite small and the fixation is very rigid. Once the load exceeds 1300N the acetabulum fracture and the displacement increases dramatically (Fig. 16). On the other hand the cementless acetabulum shows it can sustain larger compressive load of 1500N and in examining the bone surface it seems to remain intact. (Fig. 16).

4. Conclusion

This paper highlights the challenges in TKA and THR and potential experiments that can be used in validating and building dynamic models of knee and hip joints. Further work is needed to combine both of these models and create a list of potential assumptions that can serve as a basis for validation of complex models.

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