

Toward Digital Twins in Orthopedic Implants: Finite Element Analysis of Malalignment Effects in Instrumented Tibial Trays

*Leila Merzak¹, Célestin Ott¹, Elise Saoutieff¹, Pierre Gasnier¹, Vincent Elhorga¹, Sébastien Boisseau¹,
¹ Univ. Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France
leila.merzak@cea.fr*

Summary

This study investigates the impact of knee prosthesis malalignment on the strain distribution in the tibial tray. A 3D finite element model was developed to simulate all prosthetic components. Simulations showed that malalignment leads to detectable strain patterns. These findings highlight the potential to detect malalignment using a sensor-enhanced tray previously developed, which includes an integrated sensor based on a “tray–pillar–membrane” structure. These preliminary results will serve as a foundation for the implementation of a digital twin framework dedicated to alignment assessment of knee implants.

Keywords: Total Knee Arthroplasty (TKA), Finite Element Analysis (FEA), Prosthetic Malalignment, Aseptic Loosening, Digital Twin

Introduction

Total Knee Arthroplasty (TKA) is a common orthopedic procedure, aiming to restore joint function and reduce pain in patients suffering from severe knee osteoarthritis. Despite its clinical success, TKA is still associated with various complications, among which aseptic loosening being one of the primary causes of implant failure [1]. Prosthesis malalignment is one of several mechanical factors that may contribute to aseptic loosening [1]. In a recent study, Gasnier et al. [2] proposed an instrumented knee prosthesis that enables the measurement of forces and moments applied on the tibial component. However, their simulations and experimental tests were limited to idealized loading conditions involving a single, localized point load. In this study, we extend the previous work by simulating the mechanical behavior of the complete prosthetic system, with a more realistic force transmission through the femur. We first analyze the strain response of the tibial membrane under aligned conditions, and then introduce a malalignment between the femoral and tibial components to observe its effect on strain distribution.

Materials and Methods

A full 3D model of the knee prosthesis was developed, as shown in Fig 1. It includes the femur, femoral component, polyethylene spacer, tibial component, and the tibial bone. The tibial component includes an integrated sensor based on the “tray–pillar–membrane” architecture, as

proposed in [2]. In this design, mechanical loads applied to the tibial tray are transmitted through a central pillar to a deformable membrane located within the tray. Strain gauges bonded to the membrane surface measure the resulting longitudinal strain.

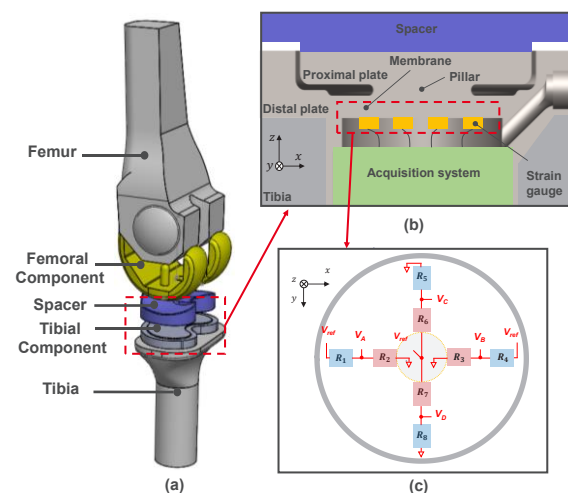


Fig. 1. (a) 3D model of the knee prosthesis. (b) Schematic cross section of the “tray–pillar–membrane” configuration. (c) Bottom view of the membrane with sensor placement.

To evaluate the strain behavior of the tibial membrane under both aligned and malaligned conditions, a finite element analysis (FEA) was performed using the prosthetic knee assembly in COMSOL Multiphysics®. Each component was assigned appropriate mechanical properties from literature as presented in Tab 1. In the

model, the connections between the femur/femoral component and the tibia/tibial component were considered fully bonded, reflecting realistic implant fixation conditions. Specifically, the lower surface of the spacer was bonded to the tibial tray, the upper surface of the femoral component was bonded to the femur, and the lower surface of the femoral component was set in contact with the tibial component under a frictionless condition due to the static conditions considered in this analysis. The bottom of the tibial bone was fixed. A refined mesh was applied around the membrane to accurately capture strain gradients.

Tab. 1: Material properties of the knee prosthetic components.

Component / Material	Young's Modulus	Poisson's ratio
Femur: Bone	20 GPa	0.45
Femoral component: Ti6Al4V, grade 23	110 GPa	0.34
Spacer: UHMWPE	0.8 GPa	0.45
Tibial Component: Ti6Al4V, grade 23	110 GPa	0.34
Tibia: Bone	20 GPa	0.45

Results

To investigate the impact of prosthesis alignment on strain distribution in the tibial membrane, three simulation scenarios were performed: a neutrally aligned configuration, a 5° valgus malalignment, and a 5° varus malalignment. These configurations are illustrated in Fig 2, representing the coronal plane alignment between the femoral and tibial components.

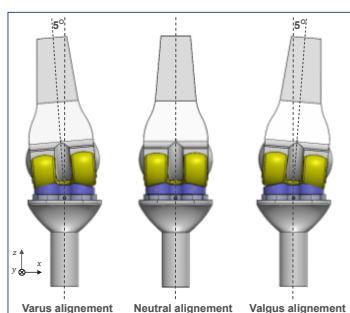


Fig. 2. Simulated alignment conditions: 5° varus, neutral and 5° valgus in the coronal plane.

In the neutral alignment configuration, the strain distribution across the membrane is symmetrical, with two balanced peaks located medially and laterally as it is shown in Fig 3. In the 5° varus configuration, the strain profile shifts toward the medial side. Conversely, in the 5° valgus configuration, the peak strain shifts laterally. These asymmetries illustrated in Fig 4

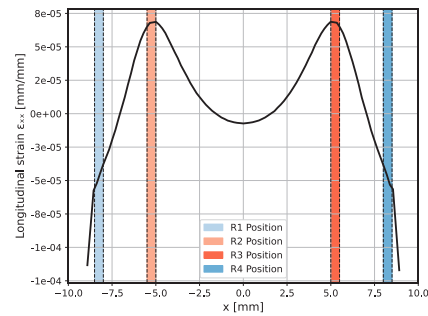


Fig. 3. FEM modeling (COMSOL) showing longitudinal strain distribution at the membrane in the neutral alignment configuration for $F_z = 180N$.

are directly reflected in the strain levels measured at the sensor locations on the membrane. This highlights the potential of the instrumented membrane, equipped with strain gauges, not only to measure the magnitude of the load [1] but also to detect prosthetic malalignment using strain data.

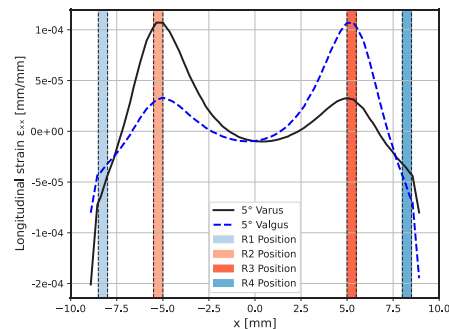


Fig. 4. FEM modeling showing the longitudinal strain distribution at the membrane under malalignment conditions for $F_z = 180N$.

These results will be further exploited within a digital twin framework developed in [3], which combine physics-based models, data-driven approaches, and real-time sensor data to detect and predict malalignment angles in knee prostheses. The simulation outputs generated in this study will serve as a training dataset for neural network models within that framework.

References

- [1] Baek, Ji-Hoon *et al.* Early aseptic loosening of primary total knee arthroplasty in patients with osteonecrosis of the knee: A case series. *Clinical case reports* (2022); doi:10.1002/ccr3.6773
- [2] Gasnier, Pierre *et al.* Design, Simulations and Tests of a Novel Force and Moments Sensor for Instrumented Knee Implants, *IEEE transactions on bio-medical engineering* (2023); doi:10.1109/TBME.2023.3289623
- [3] Merzak, Leila *et al.* "Virtual sensor" approach for damage localization in mechanical structures – methodology and experimental validation, *Engineering Research Express* (2025); doi:10.1088/2631-8695/adb6f0