Numerical study on the lubrication in total knee replacements: The influence of dynamics, geometry, material and fluid

Max Marian[1)*], Benedict Rothammer[2)], Marcel Bartz[2)],
David Nečas[3)], Martin Vrbka[3)], Markus A. Wimmer[4)] and Sandro Wartzack[2)]

[1)] Department of Mechanical and Metallurgical Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile.
[2)] Engineering Design, Friedrich-Alexander-University Erlangen-Nuremberg (FAU), Erlangen, Germany.
[3)] Department of Tribology, Faculty of Mechanical Engineering, Brno University of Technology, Brno, Czech Republic.
[4)] Department of Orthopedic Surgery, Rush University Medical Center, Chicago, Illinois, USA.
*Corresponding author: marian@mfk.fau.de

For an adequate design of total knee replacements, knowledge about stresses and lubrication conditions is vital. Within this study, a numerical model is presented and validated with experimental data. Good agreement between model predictions and experimental data as well as a strong influence of fluid, material and geometry assumptions as well as transient effects were found. It was demonstrated that the rheological synovial fluid properties have a decisive impact on the tribological behavior.

Keywords: Total knee replacement, Synovial joint tribology, Soft-elastohydrodynamic lubrication, Finite Element Method

1. Introduction

Total knee replacements (TKR) are a common surgical treatment to restore the function of the knee. Generally, TKR consist of a metallic femoral component rubbing against a polymer tibial plateau. Fundamental knowledge about present deformations, contact pressures, stresses and lubrication conditions is vital for designing TKR [1]. The objective of this study is to introduce a verified model of the soft-elastohydrodynamically lubricated TKR contacts and to analyze lubrication mechanisms and influencing factors.

2. Methods

Numerical modeling was done based upon the Finite Element Method and fully coupling the fluid's hydrodynamics (generalized Reynolds equation) with the elastic deformation of the contacting bodies. Thereby, realistic transient kinematics and loading conditions of the gait cycle (ISO 14243) were considered.
Initially, the numerical prediction was experimentally validated for mineral oil lubrication by means of knee simulator [2] with a PMMA/CoCrMo-pairing and optical fluorescent measurement technique. Further simulations were carried out to study the influence of the modeling strategy and the role of synovial fluid properties on the film formation process for the UHMWPE/CoCrMo-pairing.

3. Results and Discussion

For the numerical investigations conducted within the scope of this contribution, good agreement with experimental studies was achieved. Moreover, it was found that the complexity of numerical modeling has a strong effect on simulation results and thus on the prediction quality, especially for the fluid film height. The consideration of transient squeeze effects, non-Newtonian fluid characteristics, realistic geometries, transient kinematics and loading conditions is vital. The medial compartment was more heavily stressed and experienced higher pressures and smaller minimum film heights compared to the lateral condyle. The swing phase was determined by geometry and kinematics while load and geometry played a dominant role in the stance phase, where the overall lubricant gap was smaller. Generally, the reversal points of motion with zero entrainment speed largely affected the fluid film formation. Yet, a film collapse could be prevented by squeeze effects (see figure 1). It could be estimated that especially in the medial condyle, the stance phase and the turning points promote wear. Furthermore, the individual rheological synovial fluid parameters have a decisive influence on the lubricant film formation. Due to the wide variation between different patients [3], this can also lead to diverse tribological behavior ranging from full separation of the rubbing surfaces over the whole gait cycle to strong solid asperity contact and associated wear mechanisms.

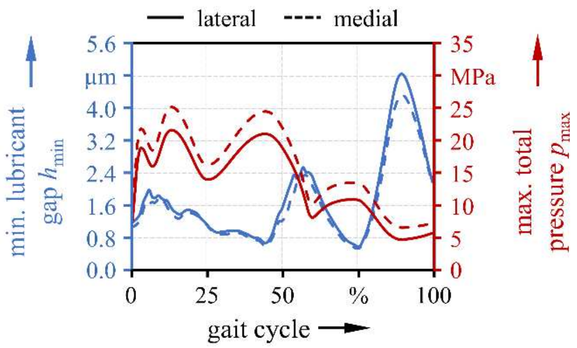

Figure 1: Minimum film height and maximum pressure evolution in the soft-EHL contact in TKRs during one gait cycle.

4. References

[1] Gao, L. et al., "Elastohydrodynamic lubrication and wear modelling of the knee joint replacements with surface topography", Biosurface and Biotribology, 4, 1, 2018, 18–23.

[2] Nečas D. et al., "The Effect of Albumin and γ-globulin on Synovial Fluid Lubrication: Implication for Knee Joint Replacements", Journal of the Mechanical Behavior of Biomedical Materials, 113, 1, 2021, 104117.

[3] Mazzucco, D. et al., "Rheology of joint fluid in total knee arthroplasty patients", Journal of Orthopaedic Research, 20, 6, 2002, 1157-1163.