A POROHYPERELASTIC LUBRICATION MODEL FOR SYNOVIAL JOINT FUNCTION AND AVASCULAR NECROSIS

B. Mathai (1), M. G. Bryant (1), R. M. Hall (2), and G. N. de Boer (1)

1. School of Mechanical Engineering, University of Leeds, Leeds, UK;
2. School of Engineering, University of Birmingham, Birmingham, UK

Introduction

The synovial hip joint provides a smooth, lubricated surface for articulation and low-friction load transmission during daily activities. However, conditions like osteoarthritis and avascular necrosis (AVN) can lead to significant degradation of the subchondral bone and cartilage, impacting joint function and tribological behaviour. The primary objective of this study is to advance our understanding by developing a comprehensive finite element model. This model incorporates principles of finite strain, porous flow, and thin-film flow to simulate the cartilage behaviour during walking, offering insights into both intact joint function and the influence of AVN on joint tribology.

Methods

The idealised geometry of the joint consisting of both the subchondral bone and the articulating cartilage was modelled in COMSOL Multiphysics 6.0 (Figure 1a), with the latter being conceptualized as a porohyperelastic material. Poroelastic modelling of the cartilage allows the free movement of fluid within the solid matrix, generating transient pressure responses to deformation and a very low friction interface [1]. To comprehensively capture lubrication dynamics, thin-film theory was integrated into the model, accounting for a thin-film region at the articulating interface [2]. Subsequently, the model underwent transient analysis, simulating loading conditions representative of a walking cycle [3] to study the tribological performance of the healthy joint and was compared with that of AVN.

Results

The simulations enabled the analysis of friction, film thickness, contact length, maximum pressure, and stress, as well as the assessment of load capacity (Figure 1). The study assessed the distribution of joint load between pressurised fluid and the solid matrix within the cartilage. Notably, the contact length demonstrated a peak occurrence and onset of contact during both the heel contact and toe-off phases of the gait cycle. During these phases, it was observed that the pressurised fluid accounted for supporting up to 94% of the joint load, while the solid component bore a minimal 6% (refer to Figure 1d). The overall friction was found to increase to 0.016 after the onset of contact. Moreover, the maximum von Mises stress in the region surrounding AVN during these peak load scenarios was measured at 1.2 MPa (Figure 1b), contrasting with a maximum value of 0.5 MPa observed in the natural joint.

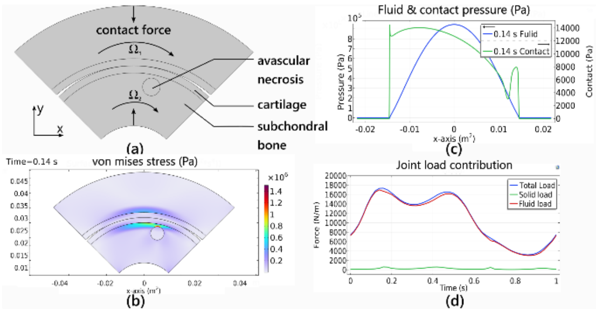

Figure 1: (a) Joint geometry compressing of two articular cartilage and bone bodies rotating under load. (b) Von-mises stress distribution in the joint model with AVN. (c) distribution of fluid pressure and contact pressure at the boundary of the intact joint during the heel contact (d) The joint load distribution between pressurized fluid and the solid matrix during the walking cycle.

Discussion

The presented model offers a pivotal tool for exploring the implications of AVN on hip joint function and the tribological behaviour of both natural and impaired joints across varied lubrication regimes. Notably, the observed monotonic decrease in friction attributed to the fluid phase aligns with existing literature [4]. The evolution of the model will focus on the integration of mechanoregulatory principles, allowing the study of mechanical stimuli's effect on AVN progression. This enhancement aims to improve predictive abilities and better guide clinical decisions and treatment strategies for AVN.

References

1. G. De Boer et al, A porohyperelastic lubrication model for articular cartilage in the natural synovial joint. Tribol. Int., 149:105760, 2020.
2. G. De Boer et al, Compliant-poroelastic lubrication in cartilage-on-cartilage line contacts. Tribol-Mat., Surf & Interf, 14:151–165, 2020.
3. G. Bergmann et al, Hip contact forces and gait patterns from routine activities. J. Biomech., 34(7):859–871, 2001.
4. Li, Junyan, et al. "Biphasic investigation of contact mechanics in natural human hips during activities." Proc. Inst. Mech. Eng. H 228(6):556-563, 2014.

Acknowledgements

This project has received funding from UKRI EPSRC under Horizon Europe Guarantee MSCA Postdoctoral Fellowships 2021 grant agreement No 101067419 (127309).