Proceedings of the 9th World Congress on Momentum, Heat and Mass Transfer (MHMT'23)
London, United kingdom – April 11 – 13, 2024
Paper No. ENFHT 333
DOI: 10.11159/enfht24.333

Design and Analysis of Direction-Dependent Flow Resistance in Custom-Engineered Geometries at Low Flow Rates

Mahdieh Mosayebi[1], Stephen J. Ferguson[1], Benedikt Helgason[1], Dominik Obrist[2]
[1]Institute for Biomechanics, ETH Zurich
Gloriastrasse 37/ 39, 8092 Zurich, Switzerland
mahdieh.mosayebi@hest.ethz.ch; sferguson@ethz.ch; bhelgason@ethz.ch
[2]ARTORG Center for Biomedical Engineering Research, University of Bern
Freiburgstrasse 3, 3010 Bern, Switzerland
dominik.obrist@unibe.ch

Extended Abstract

Joints may lose proper function due to aging, disease, and trauma, adversely affecting patients' lives. Total joint replacements are proven medical devices that can significantly restore joint function and relieve pain. However, the demands for arthroplasty have substantially increased over the past few years with a more active elderly population, while the average 15-20 year lifespan of these implants may not address the needs of younger patients [1, 2]. Studies indicated that wear and debris are the main problems leading to the failure of joint implants, however, lubrication can considerably reduce these acute complications, increase the implant lifetime, and prevent revision surgery [1, 3, 4]. Notably, natural articulating joints are self-lubricating under load due to the intrinsic poro-elasticity of cartilage tissue and the self-pressurization of interstitial fluid [5, 6]. Although lubrication plays a vital role in reducing friction and wear, no existing studies have ever considered a self-lubricating prosthesis. Therefore, we aim to design a novel self-lubricating prosthesis to mimic the natural lubrication regime of human joints. As a first step, different flow obstruction configurations within a 2D rectangular channel have been designed using COMSOL Multiphysics 6.1 to create direction-dependent flow resistance, which could control the net direction and rate of fluid exudation from a mechanical self-pressurizing bearing.

To induce direction-dependent, non-linear flow characteristics, channels with Tesla valve geometries were initially designed [7]. However, Tesla valves, designed for high velocities, do not demonstrate the same direction dependence for low physiological synovial fluid velocities induced by joint loading, in the order of millimeters per second. However, these valves inspired a design without moving structures, able to create nonlinear resistance to fluid flow through the channel. Fixed semicircular obstacles were positioned alongside the channel outlet. Dirichlet Boundary Conditions were employed for a steady-state flow to evaluate nonlinearity and asymmetry. An inlet velocity ranging from -50 mm/s to 50 mm/s with 10 mm/s intervals was applied on the fluid reservoir upper edge and the outlet pressure on the two ends of the lubrication film channel was set to 0 MPa. Subsequently, the inlet pressure was calculated. At a constant inlet velocity, the greater the inlet pressure, the higher the flow resistance. Variations in fluid flow behaviour when squeezing out to the lubrication film, compared to the flow back into the reservoir, were evaluated to characterise direction-dependent flow resistance. Results highlighted that each modification, including adding throats, extending the intermediate shell, incorporating a porous layer, adding two more intermediate shells, and reducing distances between flow obstructions, independently enhanced resistance within the channel and concurrently diminished asymmetry. Conversely, increasing the number of obstacles with a constant gap size led to a resistance decline and asymmetry enhancement.

The novelty of the present study is that the designed geometries provide distinct resistances to flows in two different directions through a channel of relevant size for joint prostheses, even at small velocity magnitudes, fulfilling a requirement that Tesla valves could not meet. These designs can be useful for many biomedical applications, including prosthesis lubrication and filtration systems.

References

[1] A. Ford, Z. Hua, S. J. Ferguson, L. A. Pruitt, and L. Gao, "A 3D-transient elastohydrodynamic lubrication hip implant model to compare ultra high molecular weight polyethylene with more compliant polycarbonate polyurethane acetabular cups," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 119, p. 104472, 2021.

[2] L. Wang, G. Isaac, R. Wilcox, A. Jones, and J. Thompson, "Finite element analysis of polyethylene wear in total hip replacement: A literature review," *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine,* vol. 233, no. 11, pp. 1067-1088, 2019.

[3] L. Gao, X. Lu, X. Zhang, Q. Meng, and Z. Jin, "Lubrication modelling of artificial joint replacements: current status and future challenges," *Lubricants*, vol. 10, no. 10, p. 238, 2022.

[4] L. Gao, D. Dowson, and R. W. Hewson, "A numerical study of non-Newtonian transient elastohydrodynamic lubrication of metal-on-metal hip prostheses," *Tribology International*, vol. 93, pp. 486-494, 2016.

[5] C. McCutchen, "Mechanism of animal joints: sponge-hydrostatic and weeping bearings," *Nature*, vol. 184, no. 4695, pp. 1284-1285, 1959.

[6] P. Lewis and C. McCutchen, "Mechanism of animal joints: experimental evidence for weeping lubrication in mammalian joints," *Nature,* vol. 184, no. 4695, pp. 1285-1285, 1959.

[7] P. Cheng, X. Jianjun, J. Kumar, H. Almujibah, H. Elhosiny Ali, T. Alkhalifah, S. Alkhalaf, F. Alturise, and R. Ghandour, "Improving efficiency and optimizing heat transfer in a novel tesla valve through multi-layer perceptron models," *Case Studies in Thermal Engineering,* vol. 49, p. 103391, 2023.