Lipid Uptake in UHMWPE under Mechanical Loading: A Combined Numerical and Experimental Study

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INTRODUCTION: Ultra-high-molecular-weight polyethylene (UHMWPE) tibial inserts in total knee arthroplasty (TKA) experience oxidation and wear, potentially accelerated by lipid infiltration from synovial fluid. The diffusion kinetics of lipid species within UHMWPE can affect the material's mechanical integrity by altering the polymer matrix through plasticization and oxidative mechanisms. This study investigates the coupled effects of mechanical stress and lipid mass transport in UHMWPE under cyclic loading through a simplified finite element framework, comparing model predictions with experimental results. The aim is to develop a computational framework to predict the effect of variables such as stress level, lipid saturation, material mechanical properties, etc., on lipid concentration, distribution, and resulting oxidation. This initial proof-of-concept study focuses on the effect of stress on saturated lipid distribution in crosslinked, remelted UHMWPE and lays the groundwork for future development of the model.

METHODS: An experimental setup was developed to apply mechanical loading and simulate lipid diffusion through UHMWPE. The setup consists of a rectangular 25x14x64mm UHMWPE sample inside a lipid bath with 0.25 wt.% lipid concentration (0.00259 g/mL). The lipid bath was created by combining 0.25wt% palmitic acid with 40wt% Tween 20 surfactant and 59.75wt% deionized water, based on ASTM 3336. A 75 kGy remelted specimen (Quadrant, Inc.) was fully submerged in the lipid bath at 37°C and compressed by a spring distributing stress through four semi-cylindrical indenters, two above and two below the sample (Figure 1). A 94.5 N cyclic load was applied to each semicylinder at 1.5 Hz frequency for 48 hours. After loading, Ester absorbance (proxy for lipid concentration) was measured from thin sections (Figure 2a) using Fourier Transform Infrared Spectroscopy (FTIR). A 2D finite element model, consisting of a single semi-cylinder and UHMWPE, was developed in Abaqus to simulate the experimental setup. The model incorporated two sequentially coupled stress and mass diffusion analyses. Stress was input to the mass diffusion analysis, where stress-enhanced diffusivity was incorporated through a pressure stress factor (κ). The UHMWPE sample was meshed with a global mesh size of 0.1mm, and 0.02mm around the loading area. Displacements were fixed at the bottom edge for stress analysis. Load was applied through an analytical rigid body to the top surface. Stress was outputted and used as input to the diffusion analysis.The lipid bath palmitic acid concentration was applied to the top surface and held constant for diffusion analysis. Concentration was output from diffusion analysis for comparison to the experimental setup.

RESULTS: The computational and experimental results had similar lipid distribution patterns (Figure 2b and 2c). In the absence of mechanical loading, lipid concentration decreased monotonically with depth. Under cyclic loading, stress fields induced heterogeneous concentration fields: lipid concentration decreased sharply beneath the contact region, with subsurface accumulation observed about 0.4 mm laterally from the centerline. This lateral accumulation occurred due to lipid displacement out of the region of maximum subsurface compressive stress, about 0.1 mm below the surface. Sensitivity analyses of the computational model revealed that solubility variations affected lipid concentration magnitude but did not alter the profile shape, while changes in diffusivity modified the concentration gradient slope. The pressure stress factor (κ) modulated mechanical stress and diffusion rate coupling.

DISCUSSION: Mechanical stress significantly influences lipid infiltration pathways within UHMWPE, promoting heterogeneous concentration fields that may explain observed oxidation profiles that vary with stress and location in retrieved knee bearings. Although the model is a simplified representation and does not replicate in vivo conditions, it provides quantitative insights into the interaction between mechanical stress and mass transport. These findings emphasize the importance of considering lipid physicochemical properties (e.g., molecular size, saturation, solubility) and mechanical loading in evaluating UHMWPE's long-term performance.

SIGNIFICANCE/CLINICAL RELEVANCE: It is essential to understand the in vivo oxidation processes and the influence of the periprosthetic environment on modern polymer bearing materials to ensure implant longevity. This study investigates how mechanical stress can change lipid mass transport into UHMWPE and provides a first step for future prediction of in vivo oxidation of polymer implant bearing materials.

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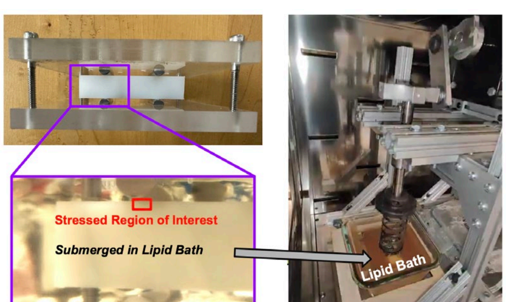
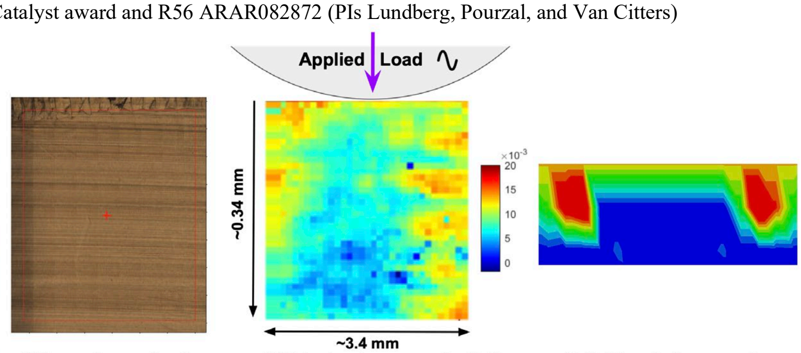


Figure 1: Experimental set-up



(a) Image of scanned section

(b) Ester absorbance normalized to the 1368 cm⁻¹ thickness proxy (arbitrary units), indicates relative Lipid Concentration

(c) Model results for same region

Figure 2: Comparison of experimental (a, b) and computational (c) results.