Cartilage Tribology: New insights into the conditions of the buried interface

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This talk challenges the conflicting assumptions foundational to predominant cartilage lubrication theories; namely, that surfaces are separated by a hydrodynamic fluid film and that surface contact creates an effectively impermeable interface. We present experimental evidence that surface hydration is the master variable for cartilage lubrication, that the hydrodynamic conditions of sliding act primarily to restore and preserve surface hydration, and that interface permeability is exceptionally low given the roughness of cartilage. To conclude, we leverage these insights to reconcile longstanding debates about the cartilage tribology and what it might imply about how best to preserve joint function and health.

Keywords (from 3 to 5 max): Biotribology, cartilage, adhesion

1. Introduction

The most common understanding of low friction in joints is that hydrodynamic synovial fluid films separate surfaces [1]. The counter-argument is that the porous cartilage surface simply soaks up any interfacial fluid and, in so doing, removes any opportunity for fluid film formation [2]. In fact, the standard boundary condition for biphasic modeling is an impermeable contact interface [3, 4]. This talk aims to resolve some of the remaining open questions and controversies over the conditions of the inaccessible interface.

2. Methods

All measurements reported in this study were conducted on cartilage explants cores from the femoral condyles of bovine stifles. Experiments were performed with contacts submerged in saline. Measurements in this study were made using a custom tribometer with in-situ deformation and optical access to the contact. Sliding experiments used a cSCA configuration designed to recapitulate hydrodynamic effects and pull-off measurements used a ¼” steel ball indentor.

3. Results

3.1 Hydrodynamic sliding

Following a period of static exudation, sliding was initiated at 60 mm/s to induce a hydrodynamic environment (Figure 1a). Hydrodynamic conditions were accompanied initially by high friction and the gradual recovery of interstitial fluid (30 μm) and low friction (0.01) after 10-20 reciprocation cycles [5].

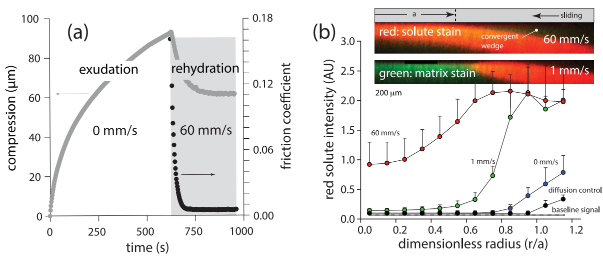

Figure 1: Effects of hydrodynamics on the recovery of fluid, solutes, and lubrication at the loaded interface.

In-situ confocal microscopy measurements revealed that interfacial uptake of a fluorescent molecule from the bath was negligible at slow speeds (1 mm/s) and important at physiological speeds (60 mm/s). The concentration gradient suggests radial (from the entrainment zone) rather than axial (from an interfacial film) flow [6]. The results suggest that friction remains high until the surface can rehydrate.

3.1 Interfacial tension

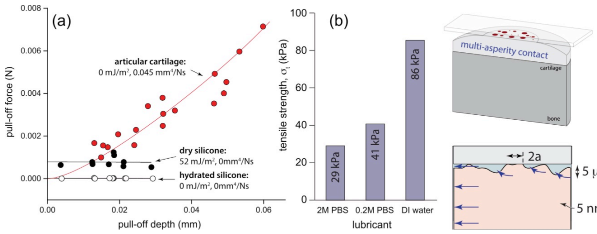

Figure 2: Interfacial tension results and interpretation.

Cartilage generates surprising pull-off forces when mated against impermeable submerged surfaces (Figure 2). The growth in interfacial tension with depth and retraction rate (not shown) is consistent with interfacial suction as opposed to adhesion. The permeability fit suggests interfacial gaps on the order of cartilage pore size, suggesting that contact completely flattens the roughness. Pull-off forces were insensitive to probe roughness and chemistry (steel or PTFE). However, it increased markedly with reduced salt content, which implicates an osmotic effect from the charged GAGs. Note that interfacial suction approaches 1 atm = 105 kPa.

4. Discussion

1) ***Rehydration*** always precedes low friction
2) ***Suction***: The interface is well-sealed; roughness is eliminated by contact
3) ***Why well-sealed***? Leverages contact area to impede loss of hydration, stiffness, lubrication.
4) ***Sliding breaks the seal:*** Fluid forced into the contact and resorbed by cartilage independently of area
5) ***Movement sustains hydration and function:*** Movement moderates the battle between the loss and recovery and fluid and its dependent functions (load support, lubrication, joint space, mechanobiochemistry)

5. References

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