Contact lubrication in human articular joints: The role of mucinous glycoproteins

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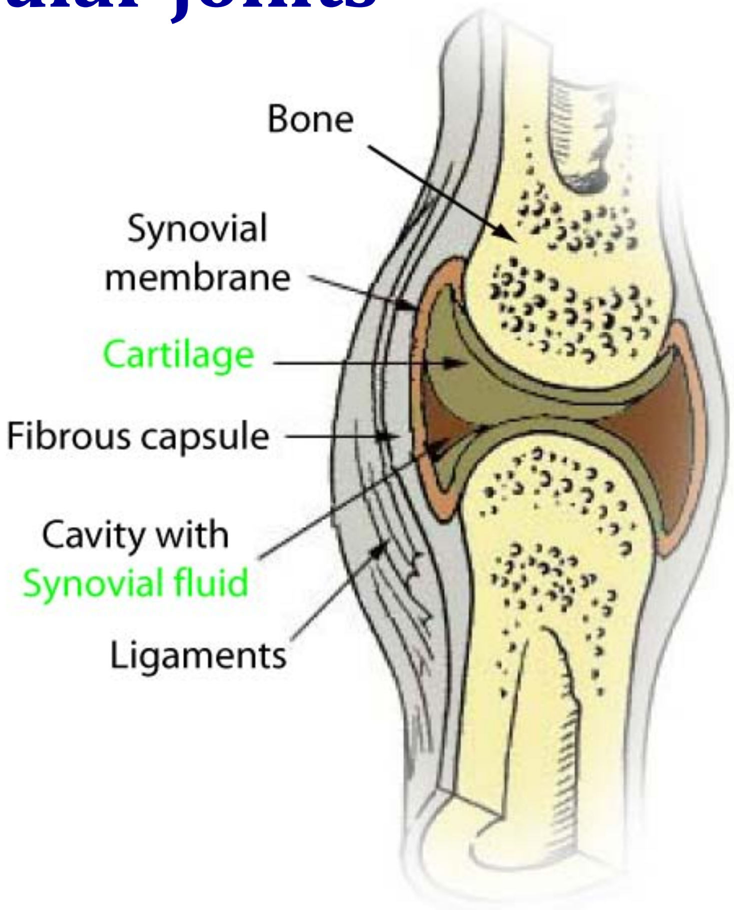
Human articular joints



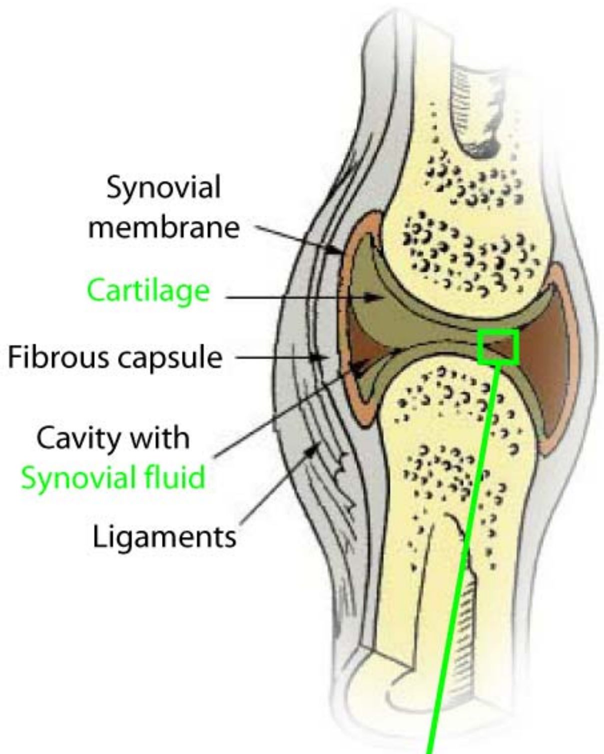
Contact between moving bones
coated with cartilage
immersed in synovial fluid

Performances
- Average/peak pressure: 1MPa /20 MPa
- Coefficient of friction: $\mu = f/F$=0.001-0.1
- Wear resistance longer than 60 years

Cartilage tissue
soft, porous and hydrated (80% water)
unlike surfaces of man-made joints

Water-based lubricants, coatings and materials
- Biocompatible devices
- Low-viscosity lubricants for MEMS, nanotech
- Microfluidics

Difficulties
- Mixed composition of tissues (H_2O, proteins, sugars, lipids, fibers, ...)
- Complex functional microstructures
- Multiple lubrication modes (boundary, ELHD, viscous, etc.) acting at different lengths and time scale



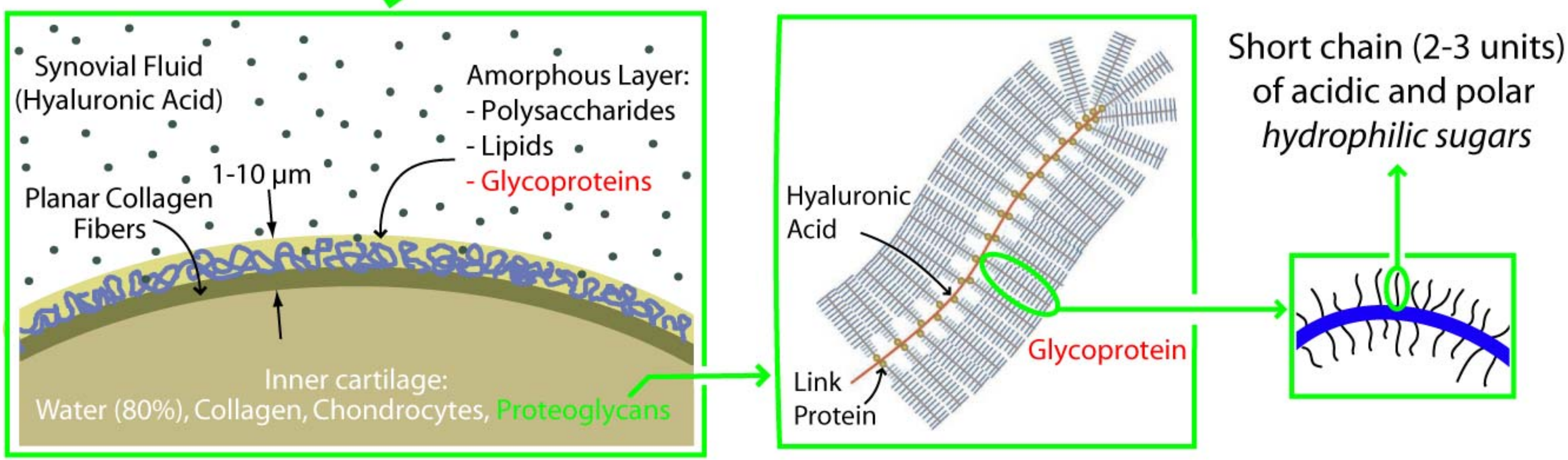
‘Biphasic’ or ‘Weeping’ lubrication

- low load, fast shear velocity, short loading time
- μm thick water film expelled from the loaded tissue

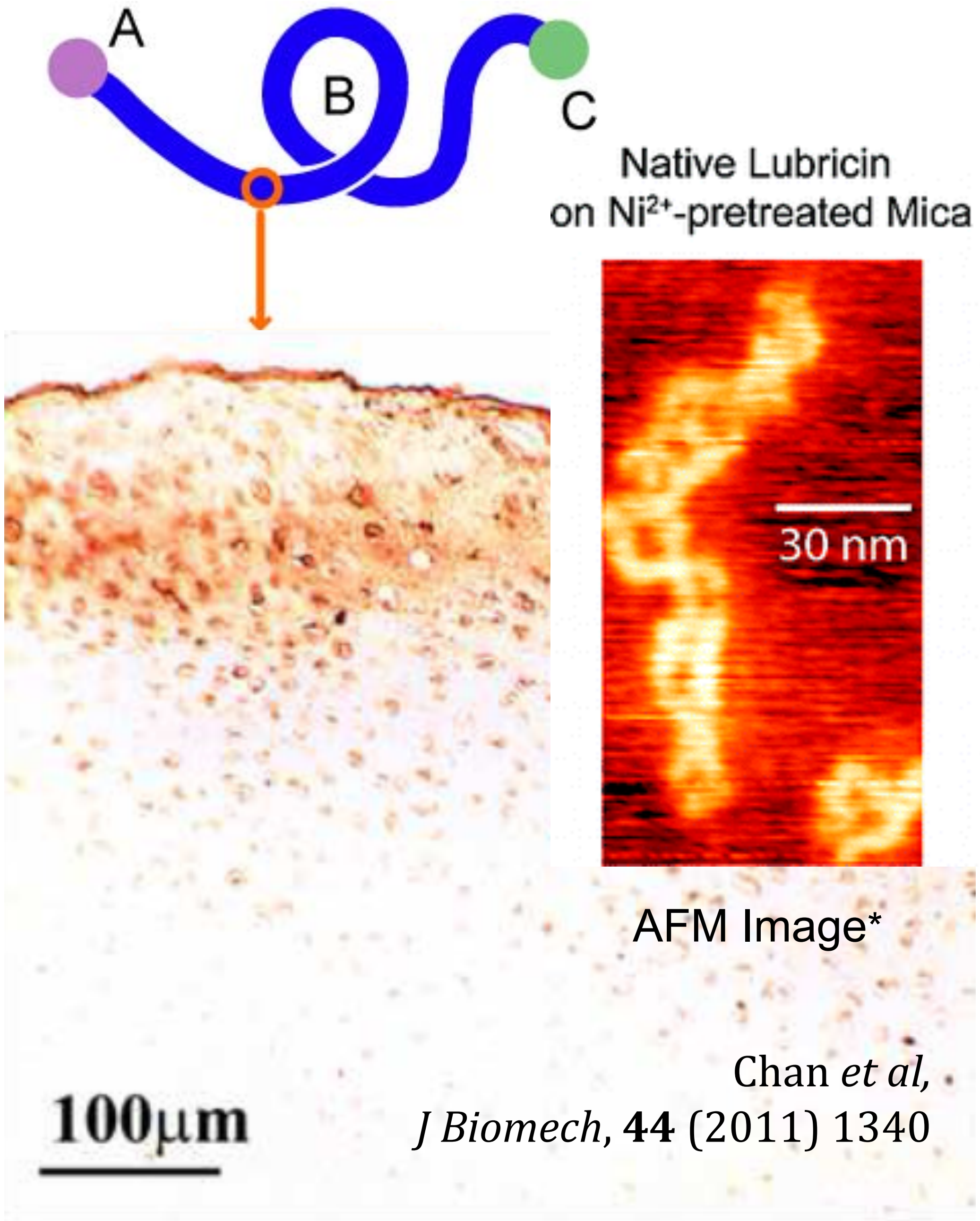
McCutchen, *Wear* **5** (1962) 1; Mow *et al, J Biomech* **17** (1984) 377; Greene, Zappone, Israelachvili *et al*, *Biomaterials* **29** (2008) 4455, *Biomaterials* **31** (2010) 3117

Contact (boundary) lubrication

- High load, slow shear velocity, long loading time
- Direct contact between ‘solid’ components of cartilage surfaces: hylauronic acid (HA), lipids, sugar-protein complexes (glycoproteins)



Lubricin (LUB, PRG4, SZP)



Chan *et al*,
J Biomech, **44** (2011) 1340

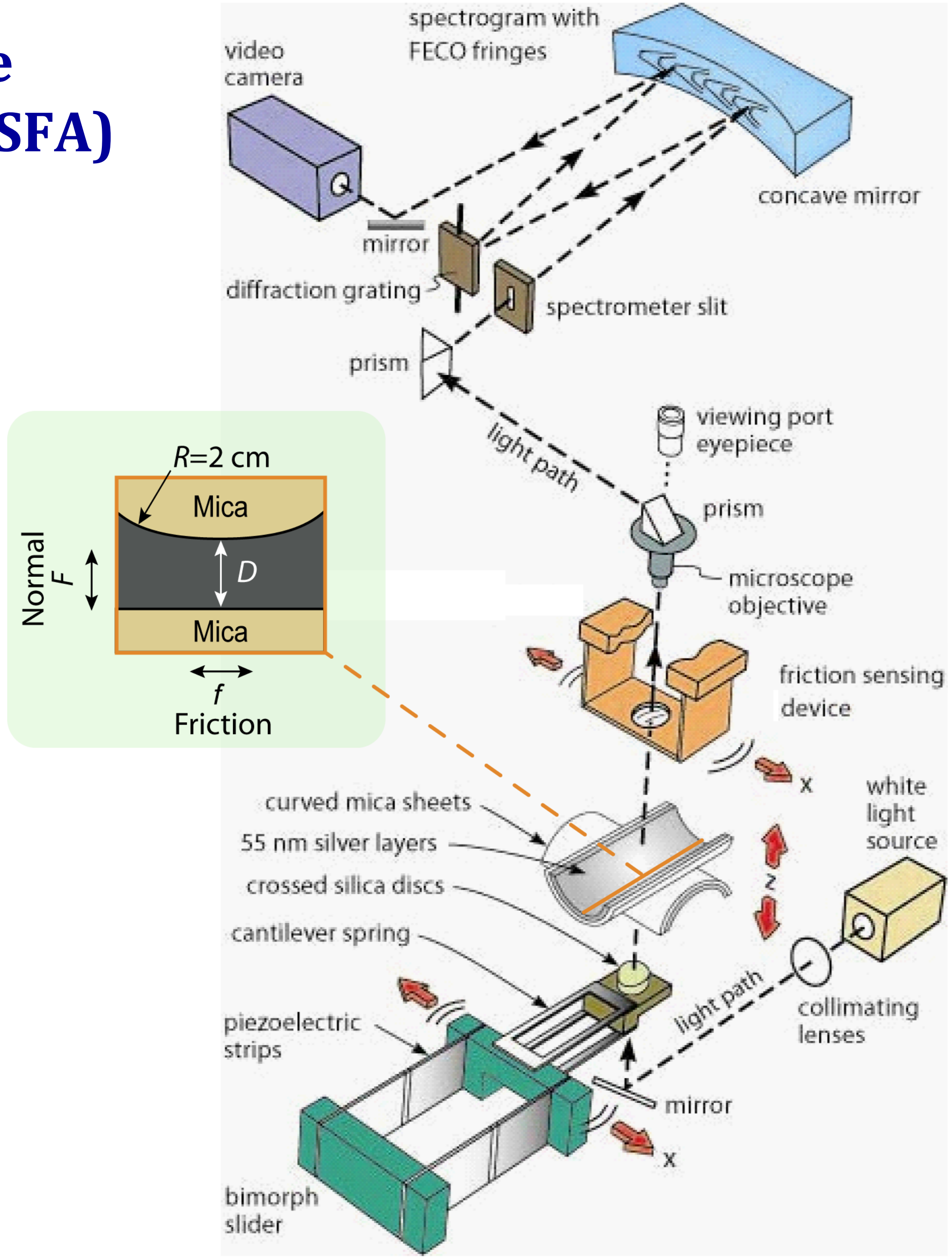
- Secreted at the cartilage surface
- Mucin-like *ABC* triblock structure
- *B*: long ($L \sim 200$ nm), densely coated with *hydrophilic* sugars
- *B*: (-) charged, rigid ($l_p \sim 10$ nm), unstructured (random coil)
- *A,C*: globular (~1 nm), (+) charged, often cross-linked (*AA, AC* or *CC*)
- *In vitro*, LUB/buffer solutions lubricate cartilage-cartilage contacts as well as whole synovial fluid.[1]
- *In vivo*, genetic deficiency of LUB produces arthritis-like diseases.[2]
- *Macroscopic* measurements so far

[1] Radin *et al*, *Nature*, **228** (1970) 377
[2] Marcelino *et al.*, *Nature Gen*, **23** (1999) 319

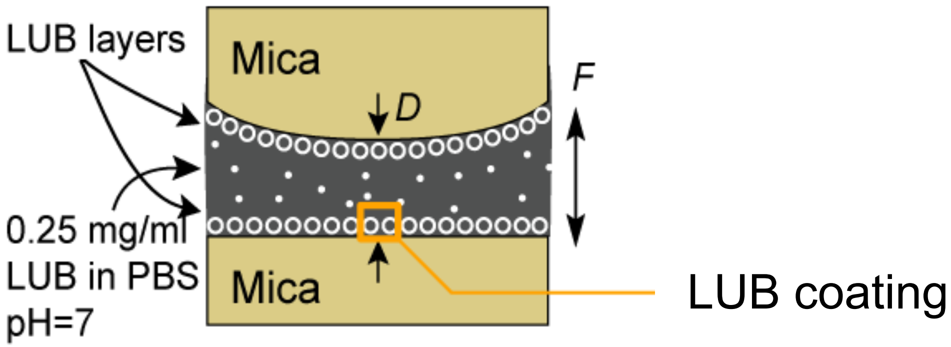
Nanoscale studies with the Surface Force Apparatus (SFA)

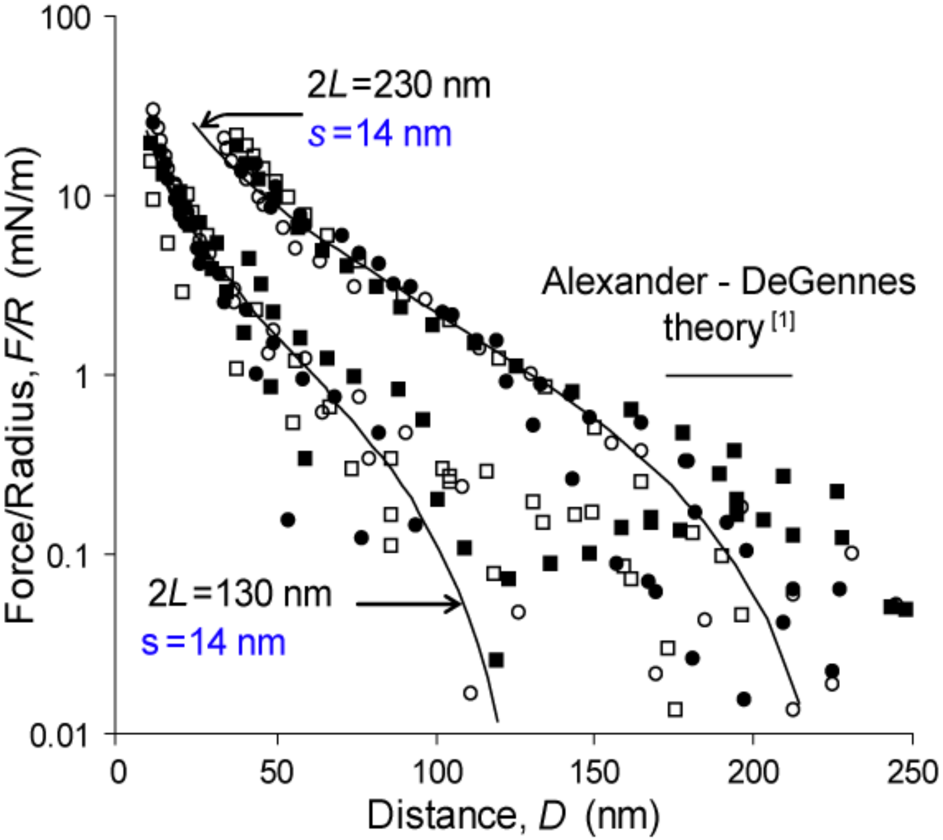
- Two glass cylinders of radius $R \approx 2$ cm crossed at 90°
- Sphere-plane geometry around single contact position
- Flexible, atomically smooth mica sheets glued on the cylinders
- Direct measurement of D by multiple-beam interferometry
- D sensitivity < 1 nm

- Microactuators move the surfaces
- Normal F and friction f forces bend springs
- Force and friction sensitivity $\approx 10^{-7}$ N



Nanomechanics of LUB coatings





- Two LUB-coated mica surfaces in physiological solution (0.2 mg/ml LUB in buffer)
- *F* vs. *D* is purely repulsive (F>0)
- $F(D)$ is reproduced in consecutive approach/retraction cycles

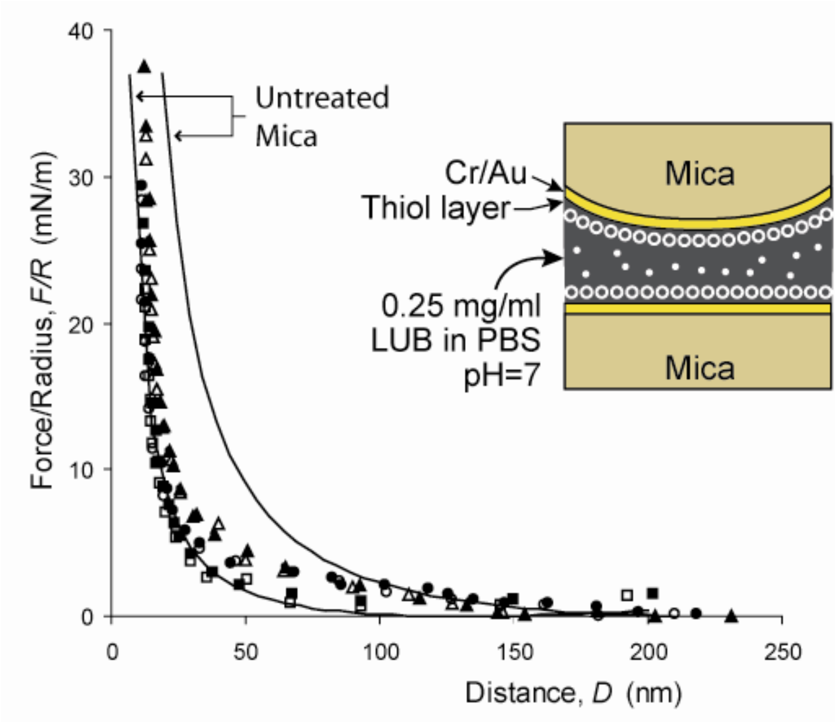
- Two distinct force curves

- Each coating is a dense "brush" of end-grafted polymers.[1]
- (+) charged *A* and C blocks adsorbed on mica: tails/loops
- (-) charged *B* block repelled by equally charged mica, stays in solution

- Loops/tails brush height: L=65/115 nm
- Grafting distance s ≈15 nm

[1] De Gennes, *Adv Coll Interf Sci*, **27** (1987) 189

Anti-adhesive properties of LUB



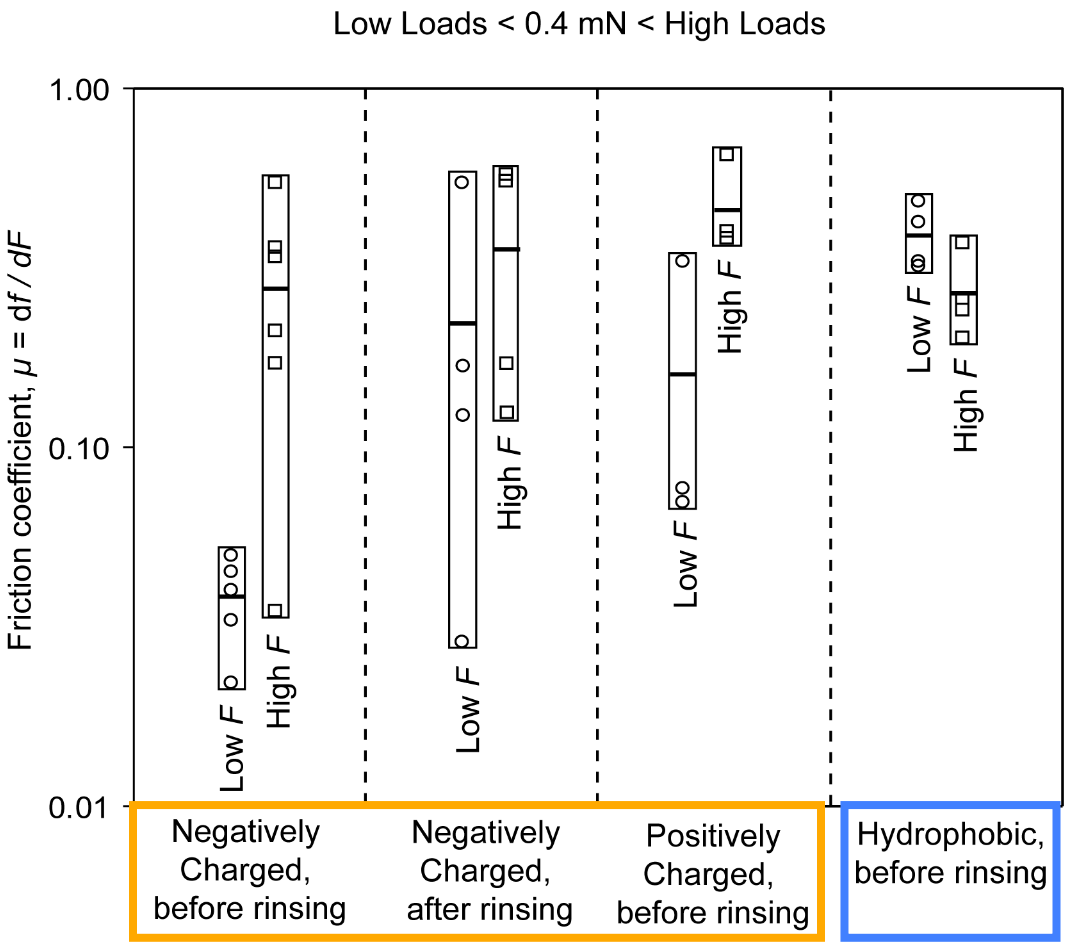
- Hydrophobic surface
  (coated with Au and alkanethiol)
- Hydrophobic aminoacids in *A* and *C* are adsorbed, hydrophilic *B* block stays in solution
- Hydrophobic binding is *stronger* than electrostatic binding, favours loop configuration → Only one curve

- Similar results on *hydrophilic* (+) charged surfaces
  (coated with polylysine or aminothiol)
- Variable loop/tail ratio and brush height

Adhesion between two brush-coated surfaces is removed

– a prerequisite for good lubrication

Nanotribology of LUB coatings *

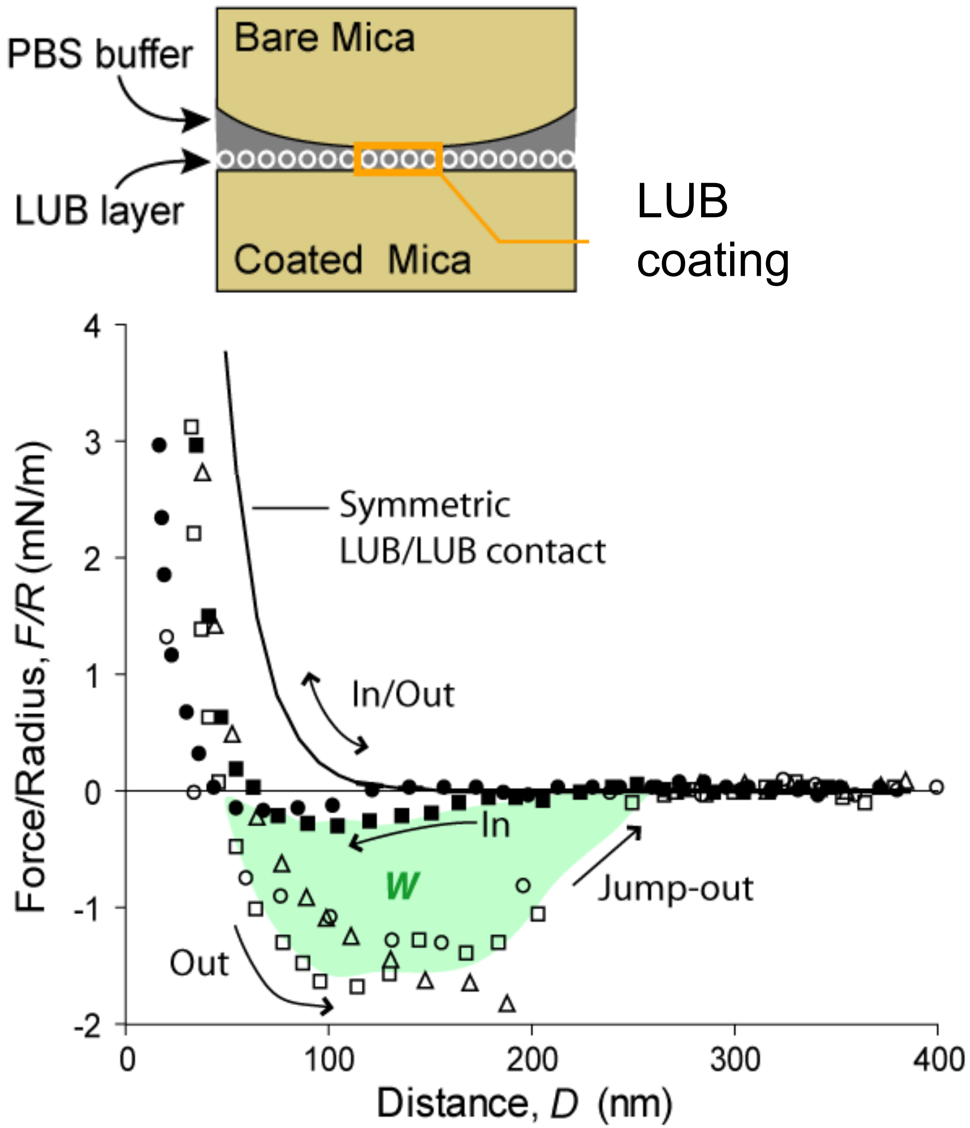


* B. Zappone *et al*, *Biophys J*, **92** (2007) 1693

- Hydrophilic surfaces (cartilage): *small* friction coefficient μ<0.1 for pressure *P*<0.5 MPa, i.e. walking conditions
- Higher *P*: irreversible damage of LUB coatings and higher friction coefficient μ>0.1
- ... but LUB coatings protect substrate from wear up to *P* = 4MPa
- Hydrophobic surfaces: high friction coefficient μ>0.1 without damage or wear for *P*< 2.5 MPa
- Substrate wear for *P* >2.5 MPa

- Weak e.l.s. interactions, *A* and/or *C* desorb during shear, small μ ← More fluidity?
- Strong h-phobic interaction, robust coating, high μ

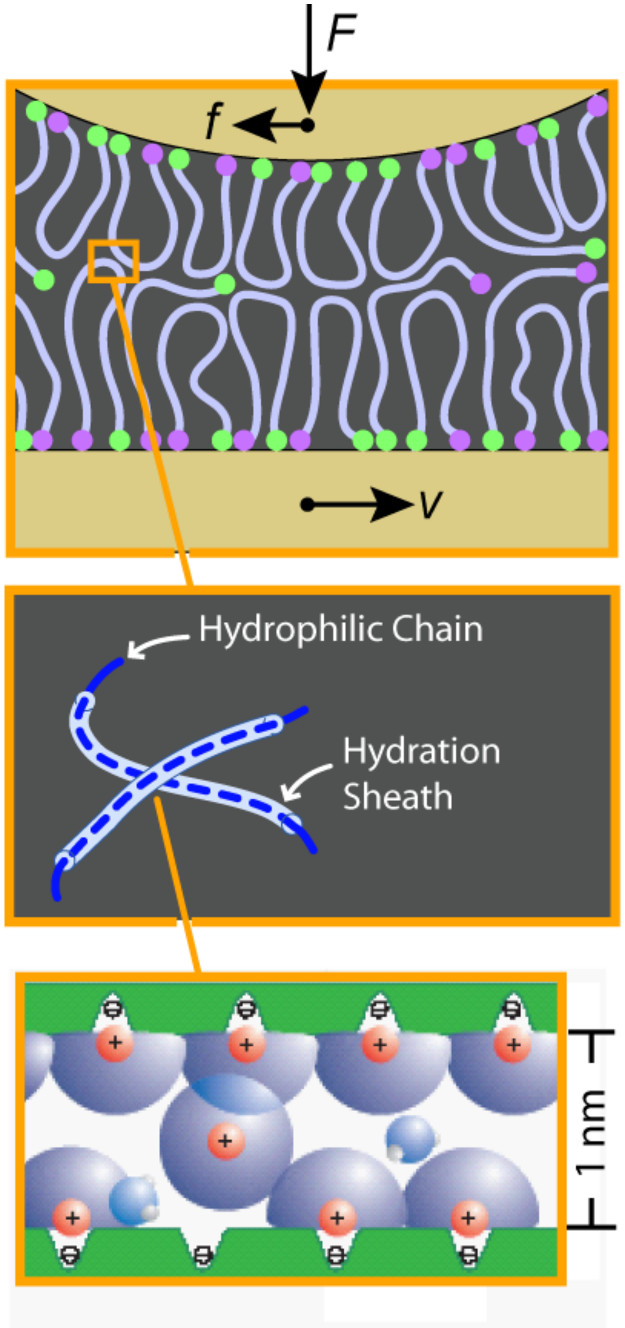
Adhesion of asymmetric contacts



- One LUB-coated mica and one uncoated mica
- Approach: repulsion and small adhesion (F<0)
- Retraction after contact: deep and long adhesive plateau
- Dynamic (non equilibrium) force, energy W dissipated in a cycle
- A and C simultaneously adsorbed on both surfaces: "bridges".[1]
- W required to elongate a bridge, break A and C adsorption bonds

[1] Wong *et* al., *Science* **275** (1997) 820

LUB brushes not expected to lubricate asymmetric contacts



Analogy with *AB* polyelectrolytes

- *Hydrophilic* (charged) *B* block
- Very low friction coeff. (μ< 0.01) at low pressures (*P*<1MPa) between two symmetric PE brushes [1]

- Small brush-brush inter-digitation, sharp and smooth shearing interface of *B* blocks
- *B* block wrapped in a "superlubricating" hydration sheath (water + ions)

- "Superlubricity" of hard hydrophilic surfaces[2]

[1] Raviv *et al, Nature* **425** (2003) 163
[2] Raviv *et al, Science* ***297*** (2002) 1540

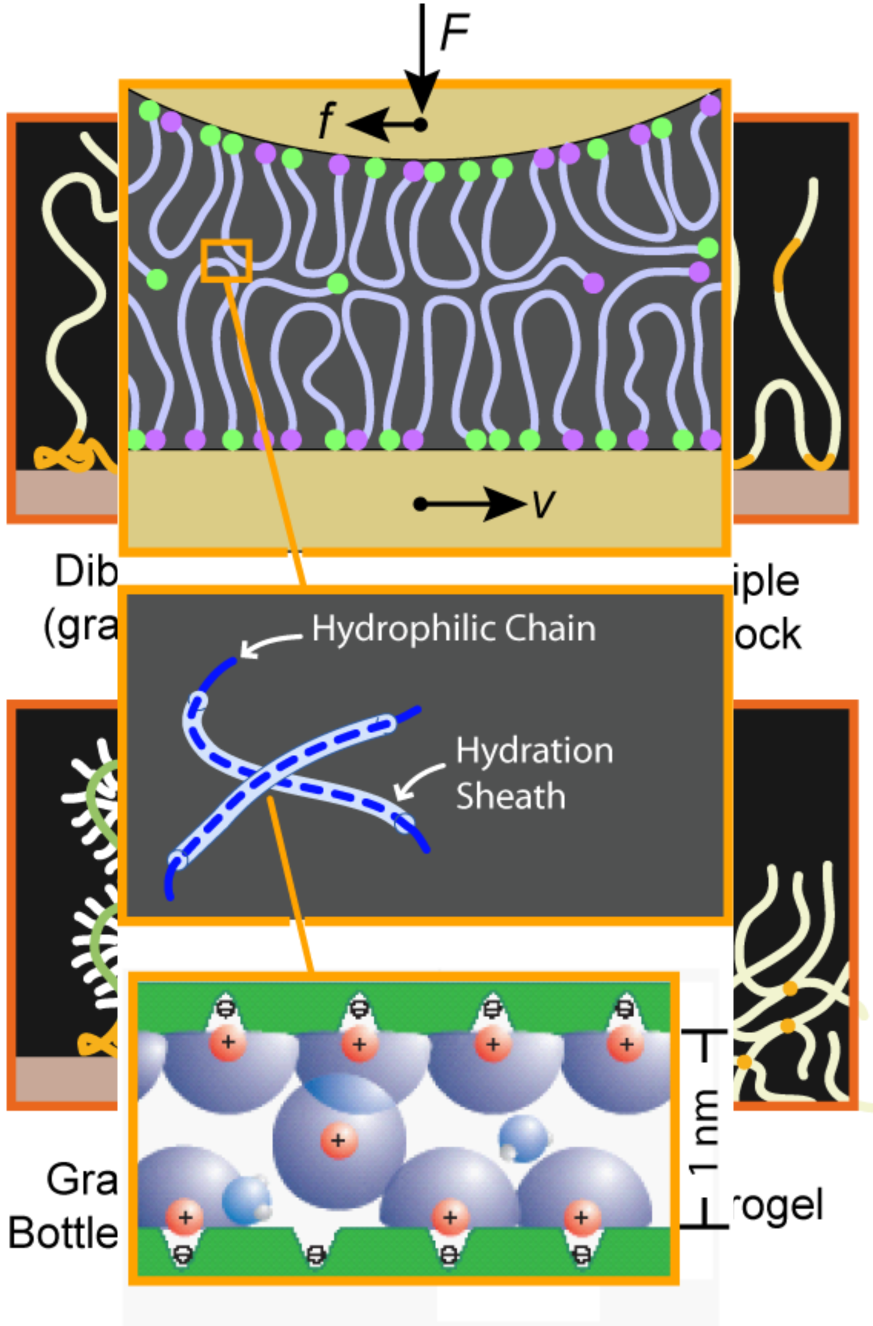
Conclusions

- Two symmetric LUB coatings reduces surface adhesion and wear
- Friction is low for hydrophilic surfaces at low loads
- Importance of molecular-scale details
- On the cartilage surface, a HA substrate/ matrix may enable LUB lubrication at low loads, providing wear resistance at high loads [3]

[3] Greene *et al. PNAS,* (2011) doi: 10.1073

Perspectives

- Biomimetic multi-block PE lubricants, with highly hydrophilic *B* block at the shearing interface.
- 19 types of mucins protect and lubricate human eyes, teeth, mouth, stomach, intestine, …
- Composition – Structure - Function?



Thank you for your attention!

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