# Micro-Scale Contact Mechanics of Cartilage: Effect of Lubrication from Acutely Injured Joints on Shear Strain

Seung Hyun Chris Kim; Benjamin L Wong; Jennifer M Antonacci; *C W McIlwraith; Robert L Sah

Department of Bioengineering & Whitaker Institute of Biomedical Engineering, University of California-San Diego
*Department of Clinical Sciences, College of Veterinary Medicine & Biomedical Sciences, Colorado State University

## INTRODUCTION

- knee joint movement involves (Fig. 1A)
  - articulation femoral condyle (FC) against tibial plateau (TP)
  - contact, rolling, & sliding of FC against TP cartilage
  - loading of cartilage in compression & shear
    - after 1 hr running: ~5-20% compression[1]
    - FC against FC cartilage[2]: ~1-5% overall shear
- cartilage shear deformation
  - regulates chondrocyte metabolism[3,4]
  - in excess; injurious and affects joint health
- synovial fluid (SF)
  - lubricates sliding cartilage surfaces
  - ↓ friction and wear[5,6]
  - maintain low shear strain ($E_{xz}$) during cartilage articulation[2]
- acute joint injury (AI)
  - SF reduces in lubricating function
    - ↑ friction between sliding cartilage surfaces[7]
    - addition of hyaluronan (HA; an SF lubricant component) to AI-SF restores lubrication function[7]
  - AI-SF may ↑ cartilage $E_{xz}$
    - ↑ cartilage wear
    - predispose cartilage to osteoarthritis (OA)

## OBJECTIVES

1) determine $E_{xz}$ for articulating human FC and TP
2) determine the effects of acute injury on SF lubricant function, and the ability of HA addition to AI-SF to restore lubricant function by comparing the following lubricants
   - phosphate-buffered saline (PBS)
   - synovial fluid from acutely injured (AI-SF)
   - AI-SF supplemented with HA (AI-SF+HA)
   - normal synovial fluid (NL-SF)

## METHODS

### *Sample Preparation (Figure 1A,B)*

- harvest 3x8x7 mm$^3$ osteochondral blocks from lateral aspects of human adult (48 ± 2 yrs) cadaveric FC (LFC) and TP (LTP)

| sample (n=4) | LFC | LTP |
|---|---|---|
| thickness (mm) | 2.1 ± 0.2 | 2.4 ± 0.3 |
| surface appearance | normal, smooth, glossy | slightly fibrillated |

- fluorescence staining: propidium iodide, 4ºC, 2 hrs
- lubricant bath + PI for ~12-16 hrs prior to micro-shear testing

### *Lubricants*

- SF aspirated from adult equine (n=4, 2-4 yrs)
- lubricants + protease inhibitors (PI) tested were
  1) PBS
  2) AI-SF: 3 wks following acute injury
  3) AI-SF+HA: added 800 kDa HA AI-SF (1mg/ml)
  4) NL-SF: aspirated from contral-lateral normal joint

### *Experimental Design*

- micro-scale shear test sequentially with (1) PBS, (2) AI-SF, (3) AI-SF+HA, and then (4) NL-SF
- rinse, re-swelling, and reincubation in PBS+PI for ~4h at 4C in between micro-scale shear testing

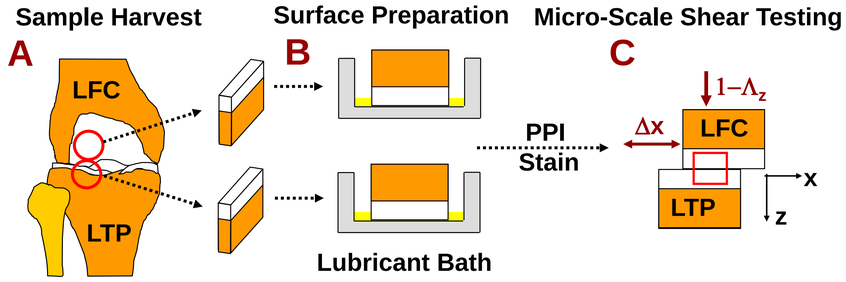


**Figure 1.** Experimental Setup involving (**A**) sample harvest, (**B**) surface preparation, and (**C**) micro-scale shear testing

### *Micro-scale Shear Testing (Figure 1C)*

- placed in LFC apposing LTP in custom bi-axial loading chamber
- video-microscopy[2]: ROI: ~1.5x1.0mm$^2$; 3 frames/s
- parameters
  - axial strain ($1-\Lambda_z$) ~15% cart. thk.
  - lateral disp. ($\Delta x$) +1 then –1 mm v = 100 μm/s
  - stress relax 1 h

### *Data Analysis & Statistics*

- ~500 cells identified & tracked on one side to determine (Fig. 2)
  - displacement
  - Lagrangian shear strain ($E_{xz}$)
- data consolidation: $E_{xz}$ averaged along normalized-depth
- repeated measures ANOVA: location & lubricant
- mean ± SEM

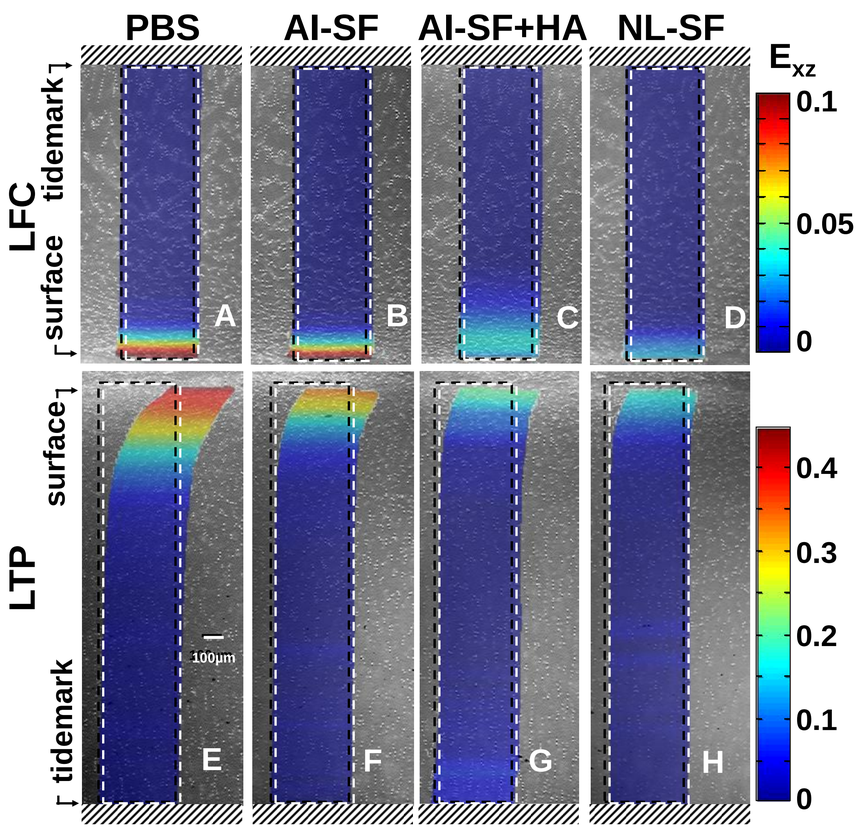


**Figure 2.** Micrographs of LFC (**A-D**) and LTP (**E-H**) sliding at the steady state peak after 15% compression and 1 hr stress relax.

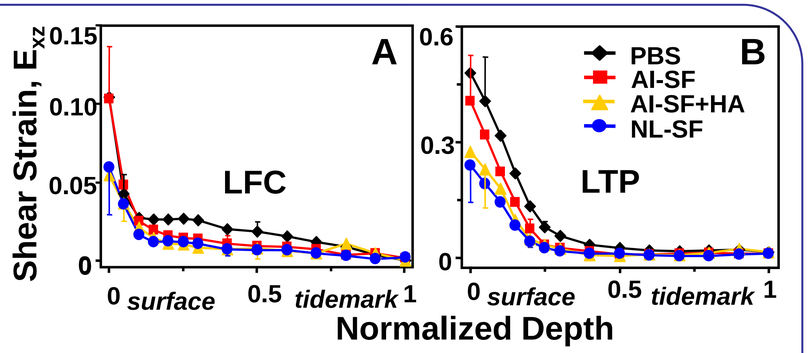


**Figure 3.** Effects of surface lubricants on shear strain vs. depth

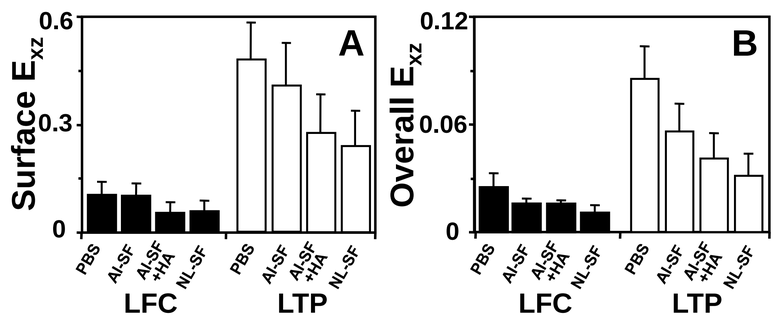


**Figure 4.** Effects of surface lubricant on (**A**) surface and (**B**) overall shear strain magnitudes.

## RESULTS

### *Local Shear Strain (Fig. 3 & 4A)*

- ↑ w/ Δx: max at surface sliding
- highest at the surface
- effect of lubricant

**LTP $E_{xz}$ (Fig. 4A)**

- NL-SF < PBS & AI-SF ($p < 0.05$)
- NL-SF ≈ AI-SF+HA ($p = 0.7$)
- AI-SF+HA < AI-SF

- LFC 3-4x > LTP ($p < 0.05$)
- **lowest near tidemark**

**LFC $E_{xz}$ (Fig. 4A)**

- similar trends to LTP but lower absolute $E_{xz}$

### *Overall Shear Strain (Fig. 4B)*

- similar trends as found for local $E_{xz}$

## DISCUSSION

- cartilage-on-cartilage micro-scale shear test
  - 1st examination of FC on TP cartilage deformation
  - mimics basic mechanics during joint movement
    - LTP $E_{xz}$ > LFC $E_{xz}$ consistent w/ their relative shear moduli[8]
    - lubricant results agree w/ surface friction studies[7]
- clinical implications
  - ↑ $E_{xz}$ w/ ↓ SF function may ↑ cartilage wear & deterioration
  - restitution of injury SF w/ HA → therapeutic treatment

## REFERENCES

[1] Kersting+, *OAC* 13:925-34, 2005. [2] Wong+, *Trans Orthop Res Soc 32:100, 2007*. [3] Jin+, *Arch Biochem Biophys* 395:41-8. [4] Nugent+, *AR* 54:1888-96, 2006. [5.] Schmidt+, *AR* 56:882-91, 2007. [6] Schmidt+, *OAC* 15:35-47, 2007. [7] Antonacci+, *Trans Orthop Res Soc* 32:156, 2007. [8] Arokoski+, *J Biomed Mater Res* 48:99-107, 1999.

## ACKNOWLEDGMENTS

CTE Lab, NIH, Cal-IT$^2$ Undergraduate Summer Research Program