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The role of lubricant entrapment at biological interfaces: Reduction of friction and adhesion in articular cartilage

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ABSTRACT

Friction and adhesion of articular cartilage from high- and low-load-bearing regions of bovine knee joints were examined with a tribometer under various loads and equilibration times. The effect of trapped lubricants was investigated by briefly unloading the cartilage sample before friction testing, to allow fluid to reflow into the contact interface and boundary lubricants to rearrange. Friction and adhesion of high-load-bearing joint regions were consistently lower than those of low-load-bearing regions. This investigation is the first to demonstrate the regional variation in the friction and adhesion properties of articular cartilage. Friction coefficient decreased with increasing contact pressure and decreasing equilibration time. Briefly unloading cartilage before the onset of sliding resulted in significantly lower friction and adhesion and a loss of the friction dependence on contact pressure, suggesting an enhancement of the cartilage tribological properties by trapped lubricants. The results of this study reveal significant differences in the friction and adhesion properties between high- and low-load-bearing joint regions and elucidate the role of trapped lubricants in cartilage tribology.

1. Introduction

Lubrication plays a critical role in preventing solid–solid interactions between contacting surfaces in relative motion. In biological systems, water and macromolecules such as lipids, mucins, and other glycoproteins provide lubrication to a variety of organs and tissues, including gastrointestinal tract, vagina, ocular surface and tear ducts, pericardium, pleura, mouth, and synovial joints (Hills, 2000; Neu et al., 2008). Articular cartilage in synovial joints is a model system exhibiting complex surface characteristics intimately related to disease of the tissue such as osteoarthritis (Neu et al., 2008). The tribological properties of articular cartilage depend on the material properties of the composite tissue and the biophysical properties of surface molecules as well as their interaction with interarticular fluid. Articular cartilage is a multiphase material consisting of a fluid phase comprising 60–85% of the tissue wet weight (ww) (Mow et al., 1992; Forster and Fisher, 1996) and a solid phase mainly composed of collagen (~15–30% ww) and proteoglycans (~4–7% ww) (Mow et al., 1992). Water and lubricant pools form between asperity microcontacts of loaded articular cartilage (Soltz et al., 2003). Various mechanisms responsible for the development of trapped lubricants have been proposed, including weeping (Lewis and McCutchen, 1959), boosted (Walker et al., 1968), and squeeze film mechanisms (Hou et al., 1992). Regardless of its origins, entrapped fluid plays a critical role in maintaining low friction during initial shear loading. Depletion of the lubricant pools by spreading and diffusion in conjunction with tissue relaxation increase the real contact area at the cartilage–cartilage interface. Under these circumstances, lubrication for maintaining low friction and protecting the cartilage against mechanical wear solely depends on the formation and timely replenishment of boundary lubricant films at the tissue surface.

The dominant mechanism of lubrication in articular cartilage depends on various factors such as contact pressure, duration of loading, and molecular constituents at the tissue surface. The pressure distribution of articular cartilage within the joint varies by location depending on physiological functional loading (Neu et al., 2007). In addition, the distributions of proteins such as superficial zone protein (Young et al., 2006; Neu et al., 2007), type I and II collagen (Lorenz et al., 2005), and glycosaminoglycans (Rogers et al., 2006) at the cartilage surface also vary by location depending on functional loading. Therefore, in this study, the friction coefficient of cartilage from high- and low-load-bearing regions of articular joints was first measured under various loads and preload durations to determine a baseline of the friction response of cartilage. The effect of trapped lubricants on the

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friction behavior of high-/low-load-bearing cartilage regions was then examined under different contact pressures by briefly unloading the samples for a few seconds to allow external fluid to flow between the depressurized cartilage and the glass countersurface and molecules adsorbed onto the cartilage surface to rearrange. To isolate lubrication provided by trapped lubricants, the duration of unloading was limited in order to minimize the amount of interstitial fluid repressurized into the tissue. Results are presented to illustrate the relative importance of trapped lubricants in articular cartilage tribology under various loading conditions affecting the intensity of asperity contact interactions and fluid exudation from the tissue.

2. Experimental procedure

2.1. Tissue acquisition

Bovine osteochondral explants were obtained from tibiofemoral joints of 1–3 week old calves, acquired from a local abbatoir within 6 h of sacrifice. Explants were harvested from medial anterior (M1) and posterior (M4) locations of the distal femoral condyles (Fig. 1A), corresponding to regions of relatively high (M1) and low (M4) contact pressure *in vivo* (Neu et al., 2007; Nugent-Derfus et al., 2007), hereafter referred to as high- and low-load-bearing cartilage, respectively. After extracting the explants with a 5-mm-diameter coring reamer, the uppermost 4 mm of the cartilage was trimmed with a custom jig. The explants were then stored in a culture medium consisting of Dulbecco's modified Eagle's medium (DMEM)/F12 at 37 °C and 5% CO_2 for 24 h before friction testing to preserve cell viability. The DMEM/F12 culture medium contained 0.2% bovine serum albumin (Sigma-Aldrich, St Louis, MO), 1% penicillin and streptomycin (Invitrogen, Carlsbad, CA), and 50 μg/mL ascorbic acid (Sigma-Aldrich).

2.2. Friction and adhesion measurements

Cartilage friction was examined with a pin-on-disk tribometer (Fig. 1B) operated in reciprocating sliding (Neu et al., 2007; DuRaine et al., 2009). Pin specimens consisted of cartilage explants affixed to acrylic pins by ethyl cyanoacrylate, while the disk specimen was a polished glass substrate. Before friction testing, the glass disk was sonicated in phosphate buffered saline (PBS) (Sigma-Aldrich). To maintain tissue hydration, cartilage explants were fully immersed in 10 mL of PBS through the duration of testing. To examine the effect of the static preload time on cartilage friction (Forster and Fisher, 1996; Basalo et al., 2006), before friction testing, the cartilage explant was allowed to equilibrate for 2, 10, or 30 min (Neu et al., 2007; DuRaine et al., 2009) under the applied normal load ($n=6$ for each load and preload time combination). The normal load was varied between 0.9 and 24.3 N, corresponding to a mean contact pressure in the range of 0.32–0.96 MPa, determined from the Hertz theory for an elastic modulus of glass and cartilage equal to 70 GPa and 1.5 MPa, respectively. Minimum values of contact pressure and equilibration time were similar to those of previous studies (Neu et al., 2007; DuRaine et al., 2009), allowing for friction testing in the boundary lubrication mode without inducing excessive suction pressures on the tissue, which could lead to the depletion of the boundary film. Since the elastic modulus of high- and low-load-bearing cartilage regions is typically equal to 1 MPa (Athanasiou et al., 1991; Froimson et al., 1997) and 2 MPa (Hayes and Mockros, 1971; Boschetti et al., 2004), respectively, an average elastic modulus of cartilage equal to 1.5 MPa was used in the calculation of the mean contact pressure. In all of the friction tests, the sliding speed was set equal to 0.5 mm/s and the wear track radius was fixed at 5 mm, resulting in a sliding distance of 7.85 mm per oscillation direction. The friction force was measured in 0.1 s intervals over a time period of 60 s using Labview (National Instruments, Austin, TX).

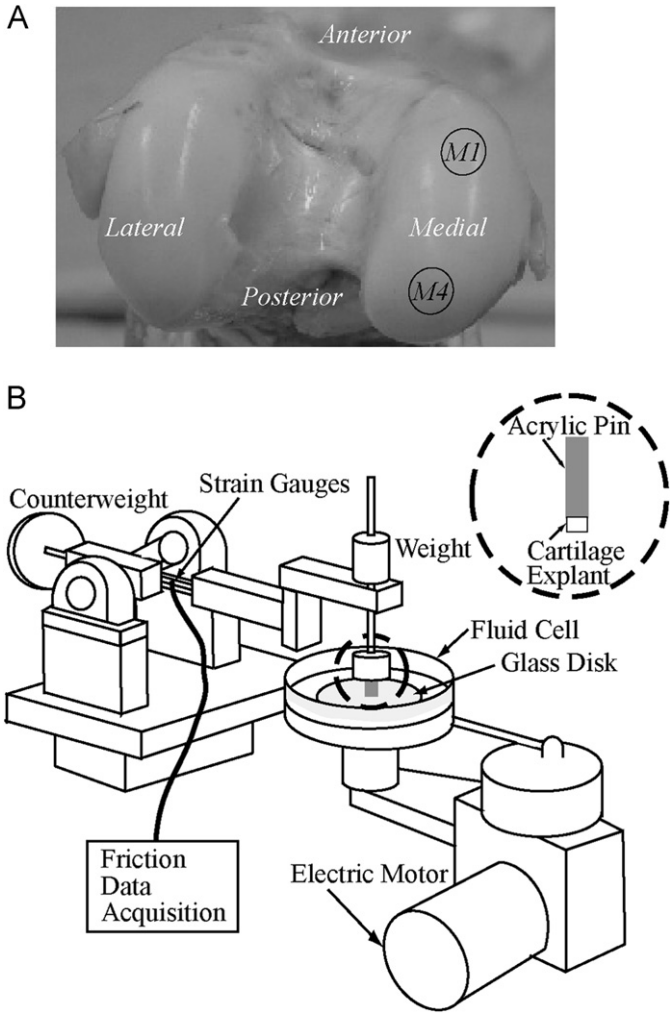

Fig. 1. (A) Samples were harvested from medial anterior locations (M1) and posterior locations (M4) of bovine femoral condyles, corresponding to cartilage regions of relatively high and low contact pressure, respectively. (B) Explants affixed to acrylic pins (inset) were mounted on a pin-on-disk tribometer for friction testing. The disk component consisted of a polished glass substrate. Both samples were fully immersed in a bath of phosphate buffered saline through the duration of testing.

A separate set of cartilage explants were used to examine the effect of trapped lubricants formed by briefly unloading the specimens to allow fluid to reflow into the cartilage–glass contact interface. Explants affixed to the pin were preloaded as described above, briefly unloaded for ~3 s (by lifting the pin with the affixed cartilage, while maintaining the explant submerged into the PBS bath), and then brought into contact with the glass disk under the applied normal load. Sliding was initiated immediately after the specimens were brought again into contact under the static load, and friction force data were acquired in 0.1 s intervals for a time period of 1 min using Labview.

The friction coefficient μ was obtained as the ratio of the measured friction force F and the total normal load, which is equal to the sum of the applied normal load L and the adhesion force L_{ad}, which acts as an additional normal load at the contact interface; thus, $F=\mu(L+L_{ad})=F_{ad}+\mu L$, where F_{ad} $(=\mu L_{ad})$ is referred to as the adhesion force during shearing under zero