Low Friction and Adhesion in Load-Bearing Articular Cartilage

INTRODUCTION: Articular cartilage provides lubrication and load-bearing properties to human synovial joints. Due to the viscoelastic nature of articular cartilage, the tissue response to loading depends on both the magnitude and duration of applied load. Because of fluid exudation and the presence of boundary lubricants adsorbed to the tissue surface, the friction coefficient of articular cartilage is high in mixed and boundary lubrication regimes are much smaller than those of conventional engineering materials in these lubrication regimes.

Friction coefficients in the range of 0.005-0.4 have been reported under different testing conditions using various counterfaces, contact loads, and durations of sliding. The increase in friction coefficient with time has been commonly attributed to depressurization of the interstitial fluid of the tissue under creep. However, the effect of the removal of key boundary lubricants during sliding, which would equally increase the friction coefficient, was largely ignored in previous studies. The typical contact pressure of articular cartilage in vivo exhibits significant variations within the joint. In addition, the expression levels of proteins, including superficial zone protein, types I and II collagen, and glycosaminoglycans also vary by location. The purpose of this study was to examine differences in articular cartilage friction coefficient from load-bearing and non-load-bearing regions of joints under varying compressive loads and equilibration time of preloading before sliding.

METHODS: Articular cartilage explants (5 mm diameter, 4 mm thick) were removed from the medial femoral condyles of juvenile bovine stifles within 12 h of slaughter. One explant from each anterior (load-bearing, M1) and posterior (non-load-bearing, M4) region were extracted and placed in serum-free, chemically-defined Dulbecco’s modified Eagle medium (D-MEM/F-12, Invitrogen), with 0.1% bovine serum albumin, 100 units/mL penicillin, 100 µg/mL streptomycin, and 50 µg/mL ascorbate-2-phosphate, prior to testing.

Friction Measurements. Friction coefficient of cartilage explants sliding against glass was measured with a pin-on-disk tribometer in reciprocating sliding mode in a fluid chamber filled with 10 mL PBS. Explants (n=6 for each combination of load and equilibration time) were equilibrated under a static load for 2, 10 or 30 min. Loads of 0.9, 1.8, 3.6, 5.4, 6.3, 12.6 or 24.3 N were applied, resulting in mean Hertzian pressures between 0.39-1.17 MPa. Sliding speed was set at 0.5 mm/s and friction force was measured for 1 min. The glass disk was sonicated in PBS prior to each measurement.

Statistics. A 3-way ANOVA was used to the determine effects of equilibration time, contact pressure, and joint location on cartilage friction coefficient.

RESULTS:

Joint Location Dependence. The friction coefficient of cartilage from load-bearing regions (M1) of the joint were significantly lower than those from non-load-bearing regions (M4) (p<0.0001) (Fig. 1). This trend was observed for all combinations of load and equilibration time. The adhesion force of M4 was also consistently higher than that of M1 for each load/time condition and tended to increase with equilibration time (Fig. 2).

Contact Pressure Dependence. The friction coefficient decreased with contact pressure, reaching a steady-state value at approximately 0.7-0.75 MPa (Fig. 1) for all joint locations and equilibration times. The friction coefficient of M1 was lower than that of M4 at all contact pressures; however, this difference diminished as pressure increased. Friction coefficients produced under 0.39 and 0.49 MPa differed significantly from those found under higher pressures (p<0.0009) whereas those produced under 0.62-0.71 MPa were significantly different from those for pressures in the range of 0.75-1.17 MPa (p<0.0073).

Equilibration Time Dependence. The friction coefficient of both M1 and M4 increased significantly with equilibration time (p<0.0001) (Fig. 1). The difference between the friction coefficients of M1 and M4 also decreased with equilibration time. The contribution of adhesion to friction was higher for M4 than M1 (Fig. 2). Adhesion decreased from 2 min to 10 min of equilibration, but increased considerably after 30 min of equilibration.

DISCUSSION: At relatively high loads and long equilibration times, the fluid in cartilage is exuded from the matrix, and boundary lubrication is the dominant mode of lubrication, where surface molecules act to protect the tissue from damage. Articular cartilage of load-bearing regions (M1) of synovial joints provides better lubrication than non-load-bearing regions (M4). This was observed under all combinations of contact pressure and equilibration time. These results may be explained by the higher concentration of boundary lubricants present at the surface of M1 cartilage. The adhesion force also tended to increase with equilibration time and was always higher for load-bearing than non-load-bearing cartilage regions at each time point. The increase in load and/or equilibration time yields an increase in real contact area as the solid matrix supports a higher fraction of the applied load due to fluid exudation from the tissue. Furthermore, under higher loads and longer equilibration times, the surface proteoglycans that aid in lubrication become more densely packed and experience higher compressive stresses that increase both adhesion and frictional resistance.

The present results underscore the significant difference in lubrication of load-bearing and non-load-bearing cartilage and the role of boundary lubricants in preventing high adhesion and friction under mixed and boundary modes of lubrication after sustained loading.


Fig 1. Friction coefficient of cartilage from load-bearing (M1) joint locations was consistently higher than from non-load-bearing (M4) locations. Friction coefficients increase with increasing equilibration time under preload and decrease with increasing contact pressure.

Fig 2. Adhesion force of load-bearing (M1) and non-load-bearing (M4) articular cartilage, measured from the intercept of the friction force versus normal load linear fits.