CARTILAGE INTERSTITIAL FLUID PRESSURIZATION IS FAR MORE EFFECTIVE AT REDUCING FRICTION THAN BOUNDARY LUBRICATION BY SYNOVIAL FLUID

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INTRODUCTION
Many studies have reported that synovial fluid (SF) reduces the friction coefficient of articular cartilage significantly by acting as a boundary lubricant [1-4]. Various constituents of SF, including lubricin, phospholipids and hyaluronic acid, have been implicated in this mechanism. Another mechanism that has been demonstrated to reduce the cartilage friction coefficient is the natural pressurization of its interstitial fluid upon loading, which helps to support most of the joint contact load and reduce the frictional force acting on the collagen-proteoglycan matrix [5-6]. This study specifically aims to characterize which of these two mechanisms is more effective.

METHODS
Twelve femoral condyles and tibial plateaus were harvested from six calf (1 month old) knees obtained from a local abattoir. They were never frozen, but stored in first physiological buffered saline (PBS) containing protease inhibitors (PI) at 2°C, for not longer than 4 days. To preserve the integrity of the articular cartilage the PBS+PI solution was changed daily. Synovial fluid was obtained from 5 adult bovine wrist joints, mixed for 10 minutes on a vortex and allowed to rest for 24 hours at 2°C prior to testing. In the first test the friction coefficient was measured by sliding the femoral condyle along the tibial plateau. Six joints (3 medial and 3 lateral pairs) were tested using SF as lubricant. In the second test, the contact region was maintained immersed in SF by adding sufficient amounts (~1 ml) at constant intervals (3 minutes); the non-articulating regions were kept moist with gauze soaked in PBS+PI. The remaining joints were tested using PBS as the lubricant. Following the first test, cartilage plugs (2±4mm) were harvested from each tibial plateau and microtomed on the bone side to obtain parallel surfaces. In the second test the friction coefficient was measured with the cartilage plugs sliding against a flat glass slide. Each plug was tested in the same lubricant as the corresponding joint.

Friction Apparatus: Reciprocal sliding motion was provided by a computer controlled sliding stage (Model PM500-1L, Newport Corporation, CA). Normal load was applied by a voice coil actuator (Model LA17-28-000A, BEI Kinetico Magnetics Division, CA) under load control feedback. Vertical and horizontal force components were measured by a multi-axial load cell (Model 20E12A-M25B, JR3 Inc., CA) mounted on the sliding stage. Vertical displacement was measured with a linear variable differential transformer (HR100, Shaevitz Sensors VA) and the horizontal displacement through a built-in function of the translational stages. Forces were converted to normal (F_n) and tangential (F_t) components to the articular surface using vertical and horizontal displacement data, and the friction coefficient was evaluated from μ=F_t/F_n.

Testing Protocol: In the first test μ was measured during continuous reciprocal sliding for 15 minutes, under a constant load of 6.3 N, over ±10 mm displacement at 1 mm/s. In the second test μ was measured under a constant load of 6.3 N for 2 hours, over ±4.5 mm at 1 mm/s; to avoid damage from wear, the waiting time between sliding cycles was increased logarithmically; μ was averaged over each back-forth cycle.

Statistical Analysis: In the first test the initial (μ_i), minimum (μ_min), and final (μ_f) friction coefficients were compared in PBS and SF with a two-way ANOVA with Bonferroni posthoc testing. In the second test the minimum (μ_min) and equilibrium (μ_eq) friction coefficients were similarly compared.

RESULTS
In the first test the friction coefficient stayed statistically constant for the duration of the experiment (no difference between μ_i, μ_min, and μ_f, p=0.80), but was statistically smaller in SF than PBS (p=0.013, Table 1). In the second test μ increased monotonically with time (Fig. 1); μ_min was significantly smaller than μ_i with both lubricants, and μ_eq in SF was significantly smaller than in PBS (p<0.001, Table 2).

DISCUSSION
In our previous study it was shown experimentally that the friction coefficient of articular cartilage increases linearly with decreasing interstitial fluid pressure [5]. The minimum friction coefficient, μ_min, is achieved immediately upon contact when the fluid pressurization is highest, while the highest friction coefficient, μ_eq, is achieved after a long duration, when the pressure has subsided. Therefore the effectiveness of interstitial fluid pressurization in reducing the friction coefficient can be assessed by the ratio μ_eq/μ_min (Table 2).

In the same way the effectiveness of SF can be assessed by the ratio μ_PREVIEW /μ_SF, equivalently achievable with μ_i, μ_eq, μ_min and μ_eq. The results of Tables 1 & 2 show that SF reduces the friction coefficient by a factor of 2 at most, regardless of the testing configuration. In contrast, interstitial fluid pressurization decreases the friction coefficient by a factor of almost 60 (Table 2). This finding demonstrates that interstitial fluid pressurization is far more effective in reducing the friction coefficient than boundary lubrication by SF. The effectiveness of fluid pressurization is only apparent from the second test, which allows the pressure to subside. In contrast, the first test, which is more physiological, since it allows cartilage to slide against cartilage with a migrating contact area, maintains a low and nearly constant friction coefficient due to persistent fluid pressurization [7]. The results of this study suggest that restoring normal tribological function in osteoarthritic joints may not be achieved simply by injecting a synovial fluid-like lubricant in the joint. In order for cartilage to pressurize sustainably upon loading it must maintain its mechanical integrity, which is generally compromised in osteoarthritics. Therefore treatment modalities should aim to repair cartilage using tissue engineering methods which reproduce the native mechanical properties as closely as possible.

ACKNOWLEDGEMENTS
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REFERENCES
1. Linn FC, J Biomech 1968;1:191-205

Table 1: Friction results for the tibio-femoral joint. †p<0.005 SF vs PBS.

<table>
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<th>μ_i</th>
<th>μ_min</th>
<th>μ_eq</th>
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<tbody>
<tr>
<td>PBS</td>
<td>0.02±0.008</td>
<td>0.02±0.009</td>
<td>0.02±0.009</td>
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<tr>
<td>SF</td>
<td>0.017±0.004†</td>
<td>0.014±0.008†</td>
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Table 2: Friction results for the tibial cartilage plug against glass. *p<0.005 μ_MIN vs μ_EQ, †p<0.005 SF vs PBS.

<table>
<thead>
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<th>μ_MIN</th>
<th>μ_EQ</th>
<th>μ_EQ/μ_MIN</th>
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<td>PBS</td>
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<tr>
<td>SF</td>
<td>0.0015±0.0003*</td>
<td>0.089±0.008†</td>
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Fig. 1: Average and standard deviation curves of the friction coefficient of tibial cartilage plugs against glass, in SF or PBS.