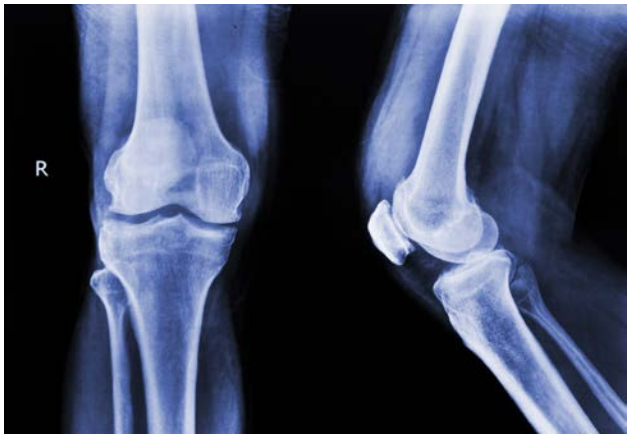
Biotribological Investigation of Cartilage

Relevant for: Tribology, Implants, Medical Engineering

Tribology combines the studies of friction, wear and lubrication. In biomedical research, tribology is employed to understand naturally occurring motions between tissues (e.g. joint surfaces) and organs (e.g. pleural tissue during breathing), but also for artificially created boundaries between natural and implant surfaces (e.g. hip implants). In order to improve the surface properties of implant materials it is crucial to understand the properties of the natural material before a suitable substitute can be developed.



Cartilage is a prominent example for a tissue, which is constantly exposed to friction forces and, for which a suitable surrogate material is still missing. Many research groups worldwide try to mimic the tribological properties of native cartilage. Yet, our understanding of the microscopic principles that constitute the unique material properties of cartilage is still limited. Hyaline cartilage lines the articular surfaces of joints and provides long-lasting ultralow friction and negligible wear under various velocities and normal loads. However, 27 million people in the United States suffer from osteoarthritis, a degeneration of articular cartilage (1).

Thus, there is high demand for a cartilage substitute material that reproduces, or at least approximates, the tribological properties of cartilage. Adequate surrogate material design requires reliable test setups, that allow for detailed characterization of tribological properties of native cartilage.

Standard test setups for evaluation of cartilage friction are currently pin-on-disk and pin-on-plate designs. These setups are mostly used with pairings of cartilage against glass, steel or cartilage. Mimicking the physiological loading of cartilage, oscillatory sliding motions with amplitudes of a few millimeters are used, and accessible sliding velocities are typically limited to 0.1^{-5} mm/s. In order to gain more insight into the frictional properties of cartilage, a different test setup allowing a broad range of sliding velocities under precise control of the test conditions would be helpful.

Here, we describe a rotational tribology setup that enables investigation of cartilage under defined conditions both in oscillatory or rotational motions. This setup allows performing friction measurements over a broad range of sliding velocities and normal pressures.

1 Experimental Setup

1.1 Sample Preparation

Osteochondral cylinders (bone cylinders with a layer of cartilage on top) with a diameter of 5.5 mm were harvested from patellofemoral grooves of lambs. Prior to tribological analysis, the samples were incubated in lubricant for 1 h. Afterwards, the cylindrical samples were placed into the sample holder (Figure 1a), and each sample position was adjusted with set-screws (Figure 1b). Thereby, it was ensured that only the bone segment was buried into the bores, so that the cartilage layer could still be probed without lateral confinement by the lubricant chamber.

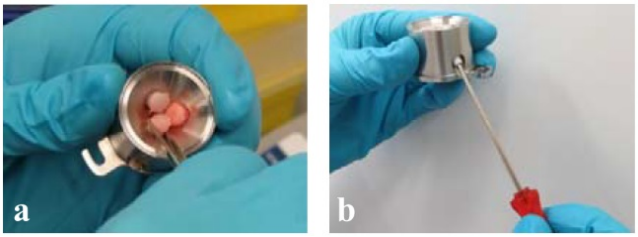


Figure 1: Sample holder setup: 3 cylindrical samples are placed into the sample holder (a) and their vertical position is adjusted with set screws (b).

1.2 Tribology System

Friction measurements were conducted using an MCR rheometer equipped with TruStrain™ control and the Tack/Squeeze/Normal Force extension package. A tribology system was mounted onto this rheometer by replacing the Peltier plate that is typically used for rheology. In the sample holder of this tribology system, three osteochondral cylinders were placed as a sample set, and this sample set was probed simultaneously using a ½-inch glass sphere as the tribological counterpart (Figure 2).

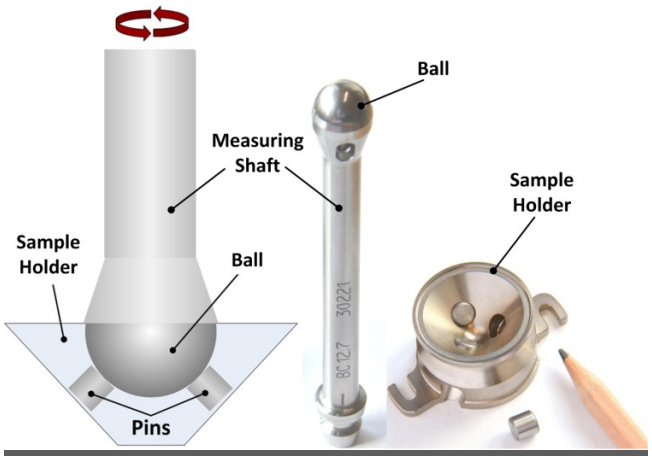


Figure 2: Schematic illustration of the tribological test setup probing a set of three osteochondral cylinders with a ½-inch glass sphere.

Figure 3: Anton Paar MCR with a tribological measuring cell.

The tribo unit supporting the sample holder (Figure 4a) comprises a lateral spring system, which ensures that the applied normal force is distributed evenly onto the three cylindrical samples so that lateral shear is minimized. For the measurements shown here, a normal force of 6 N was applied to the sample set, resulting in a normal force of 2.8 N acting on each specimen surface. Force distribution was experimentally verified to be even by obtaining colored imprints of stained cartilage samples onto the glass sphere (Figure 4b).

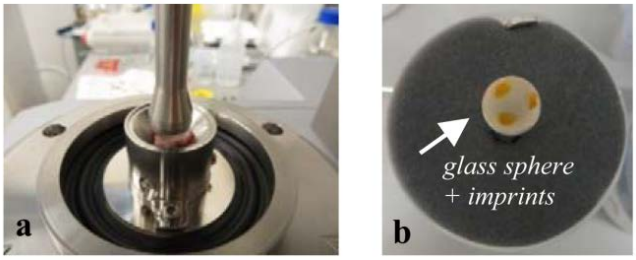


Figure 4: Tribology setup with mounted sample holder and lowered measuring head (a) and evaluation of the contact area between cartilage surface and glass sphere (b).

For each cylindrical sample, the applied normal force should result in an approximate contact pressure of 0.1 MPa. Under physiological conditions, contact pressures of 1 to 5 MPa with peaks of up to 18 MPa (during standing-up) are reported (2). For in-vitro frictional tests, contact pressures between 0.1 and 1 MPa are commonly used (3), (4).

2 Results and Discussion

In a first set of tests, the new setup for cartilage specimens was compared to the classical ball-on-3-plates measuring test setup using Teflon plates against a glass sphere. A classical Stribeck curve was recorded by implementing a logarithmic speed ramp with an increasing rotational speed from 10^{-4} to 10^{2} mm/s. A normal force of 6 N was applied, measuring point duration was set to 1 s, and 50 points per decade were recorded. Both systems were lubricated with deionized water containing 154 mmol/L NaCl, and the tests were run at room temperature (21 °C).

As shown in Figure 5, a classical Stribeck curve was obtained for the PTFE plates: the friction coefficient increased weakly up to a speed of 0.001 mm/s (boundary lubrication) followed by a mixed lubrication regime (0.001 to 0.1 mm/s), and a hydrodynamic lubrication regime with an increasing friction coefficient. In contrast, for the cartilage samples, the friction coefficient increased continuously until it reached a maximum at a speed of 25 mm/s and decreased afterwards.

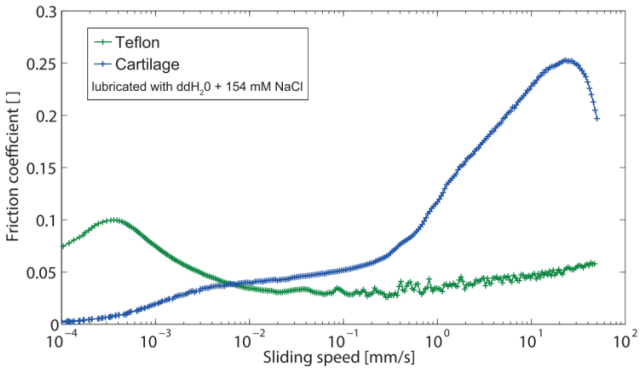


Figure 5: Comparison of friction coefficients measured for PTFE plates and cartilage samples against a glass sphere.

The low frictional properties of cartilage are highly dependent on the fluid pressurization of the interstitial fluid inside the cartilage matrix. Under constant load this mechanism diminishes, fluid is pressed out of the material and the load is fully taken by the matrix. Therefore, the friction coefficient increases over time. In order to take account for this time-dependence of the friction coefficient of cartilage, the friction coefficient was monitored at distinct speed levels. The sample sets were measured using the following rotational speeds: 0.01 mm/s, 0.1 mm/s, 1 mm/s, 10 mm/s and 50 mm/s. For each speed level, a test period of 1 hour was chosen. Between measurements, specimens were unloaded for 30 minutes to ensure full material recovery. As expected, for each speed level, the friction coefficient increased over time starting at initial coefficients of 0.02 to 0.16 and rising to plateau values of 0.1 to 0.6.

Based on these results, the equilibrium friction coefficient was averaged over the last 10 seconds of the measurement interval. As some of the measurements did not reach a plateau within 1 hour, the plateau friction coefficient was extracted by fitting an exponential rise $(y = a - b \cdot e^{-c(x)})$ to the experimentally determined curve as shown in Figure 6. Such a fitting procedure is preferable to a longer measurement period to minimize the influence of wear and resulting abrasion on the friction coefficient.

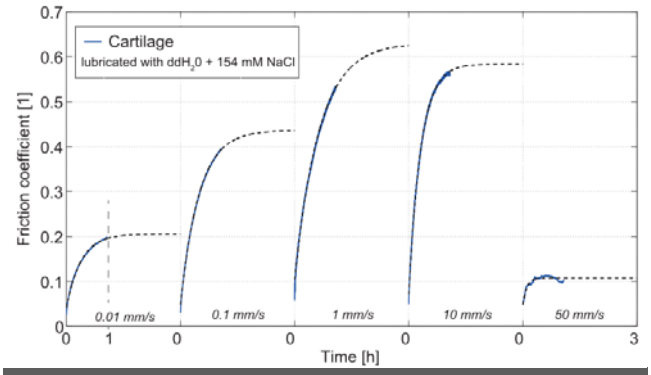


Figure 6: Cartilage friction over time at different rotational speed levels.

To identify the lowest speed level the rheometer can successfully control during a friction measurement, measurements at constant speeds were performed for 30 minutes. In Figure 7, these measurements are displayed as vertical black lines, where the height of the line represents the plateau friction coefficient reached at 30 minutes. Whereas the static friction was not overcome for rotational speeds controlled to 10^{-5} mm/s and 10^{-4} mm/s, the rotational speed was nicely held constant for speed levels of 10^{-3} mm/s and larger.

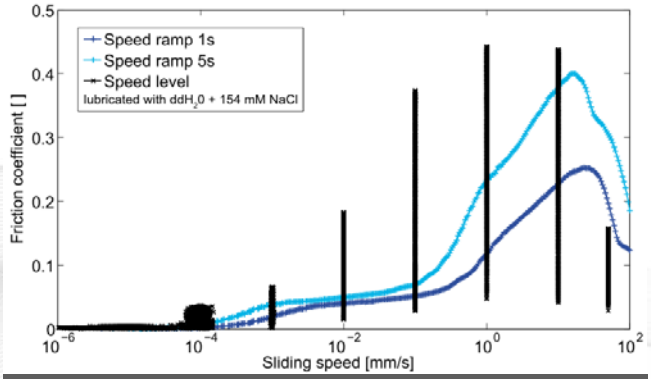


Figure 7: The measuring accuracy depends on the rotational speed. Friction measurement results obtained from speed ramps and from measurements at constant speeds are compared.

In the next step, the two methods for determining the friction coefficient of cartilage were compared. In addition to the initially recorded speed ramp, a second speed ramp with an increased sampling time of 5 s was recorded. This measurement protocol clearly led to increased friction coefficients compared to the speed ramp performed with a sampling time of 1 s. This result correctly reflects the strong time dependence of cartilage friction as depicted in Figure 6. In conclusion, the friction values obtained by applying a speed ramp are overall lower compared to the equilibrium friction coefficient obtained from measurements at distinct speed levels. However, the overall trend of the dependence of the friction coefficient on the rotation speed is preserved.

As stated before, the friction coefficient of cartilage depends on the material's ability to pressurize the fluid phase inside the cartilage matrix. This process depends on the osmotic pressure (Donnan equilibrium) that arises from the negative fixed charge density in the matrix, and the ion concentration in the fluid phase. The osmotic pressure gradient can be tuned by changing the salt concentration of the lubricant. It has been reported that a higher salt concentration of the cartilage lubricant leads to a lower equilibrium friction coefficient, whereas a low ionic strength increases friction (5). This finding is in good agreement with our results as shown in Figure 8.

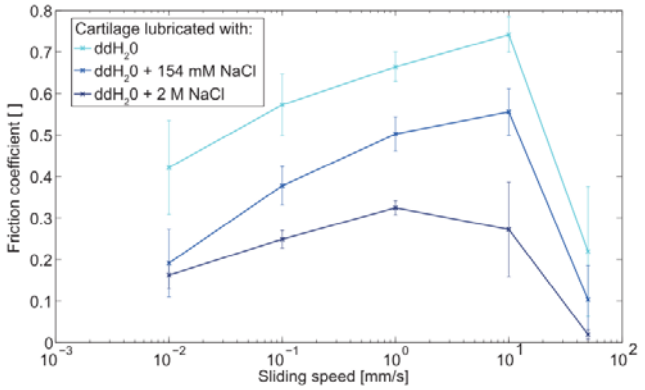


Figure 8: Comparison of cartilage friction using lubricants with differences in their ionic strength.

The error bars in Figure 7 represent the standard deviation in those friction measurements (N = 4) and demonstrate good reproducibility of the measurements considering the relative high intrinsic variability of biological samples.

3 Summary

The described test setup enables evaluation of the frictional properties of osteochondral cylinders under well-defined conditions. The influence of individual variables, e.g. lubricating fluid, test duration, and contact pressure on the friction of cartilage can be compared systematically. This allows new insights into the mechanism establishing the ultra-low friction of cartilage. In addition to the material characterization of biological tissue, this measurement technique can be easily adapted and used to characterize explant materials (harvested during replacement surgeries) or tissue-engineered constructs. This enables evaluation of currently employed cartilage repair techniques prior to replacement surgeries, as well as of the tribological properties of newly designed materials for future treatment strategies.

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