

## **CHAPTER 5**

### **DISCUSSION**

#### **5.1 OVERVIEW OF RESULTS**

The results obtained using several analysis techniques have provided varying levels of evidence of differences between the lubricants and loads that have been tested for comparison in this study. Analysis of the friction alone has shown a significant difference between loads, but no significant differences resulting among the different lubricants used. The comparison of total changes in displacement has shown similar results.

Analysis of cartilage wear by hydroxyproline measurement showed statistical significance between loads, but not among lubricants. Visible differences, however, were observed among high-load (65 N) test results, showing the highest wear in saline tests, the lowest in synovial fluid tests, and an intermediate level of wear in hyaluronic acid tests.

Analysis of the worn cartilage surfaces using scanning electron microscopy, as well as histologic sections, revealed visible differences, both between loads and among lubricants.

The opaque film that appeared on saline and hyaluronic acid tests also provided information about the differences between lubricants. Although these films appeared equally during low and high load tests, they did not appear in any tests in which synovial fluid was the lubricant.

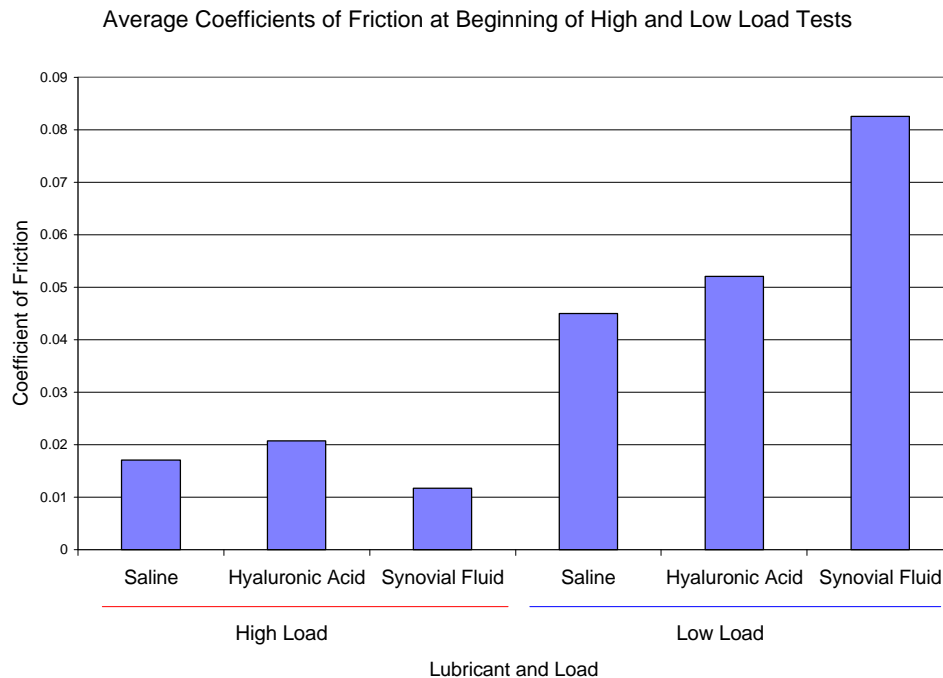
## 5.2 FRICTION

The values of friction coefficients (Figures 4.1 - 4.3) increase by a factor of ten or more over the duration of each test. The coefficient of friction began at a low level in each test, then increased rapidly during the first 60 minutes to level out to a constant value for the remainder of the test. Although the coefficients of friction depended on the applied load, this trend was observed in all of the 24 tests that were performed.

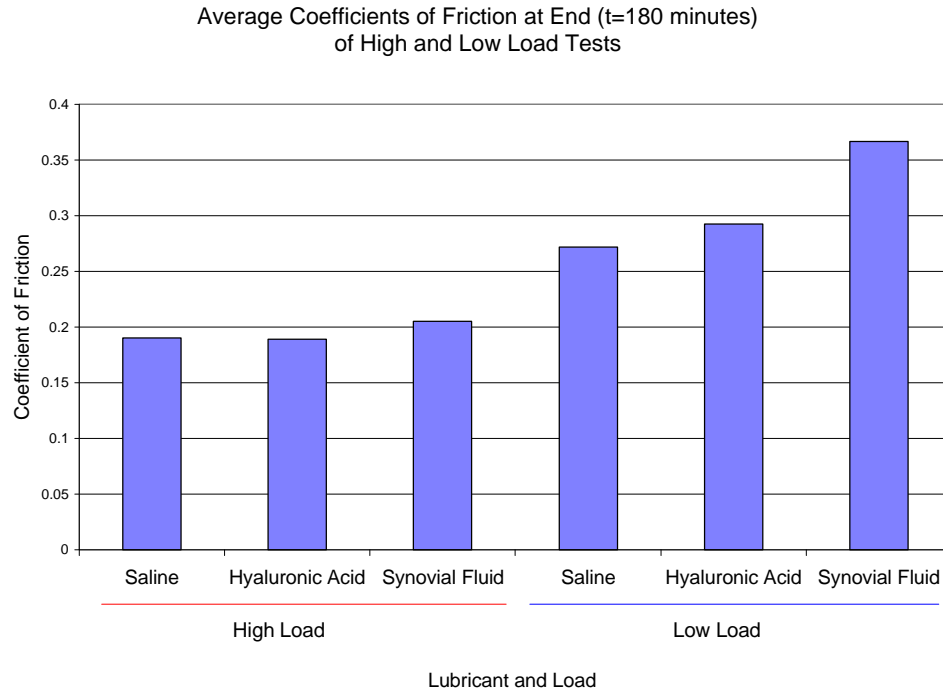
One explanation of this increase in friction concerns the mode of lubrication that exists at different times during the test. If the sliding surfaces were to begin their relative motion separated by a thin film of lubricant, a low coefficient of friction would be observed early in the test. Thinning of this lubricant film with time would result in a significant increase in friction later in the test as the system progressed into the boundary lubrication regime.

The observed increase in the friction coefficient could also be a consequence of the wearing away of the protective surface zone of the cartilage, in which the collagen fibers run parallel to the cartilage surface. Removal of this zone could result in a rapid increase in the friction coefficient, as was observed in this study.

Figures 5.1 and 5.2 show the average coefficients of friction at the beginning ( $t=0$  minutes) and end ( $t=180$  minutes) of high and low load tests.



**Figure 5.1: Average Coefficients of Friction at Beginning of Tests**



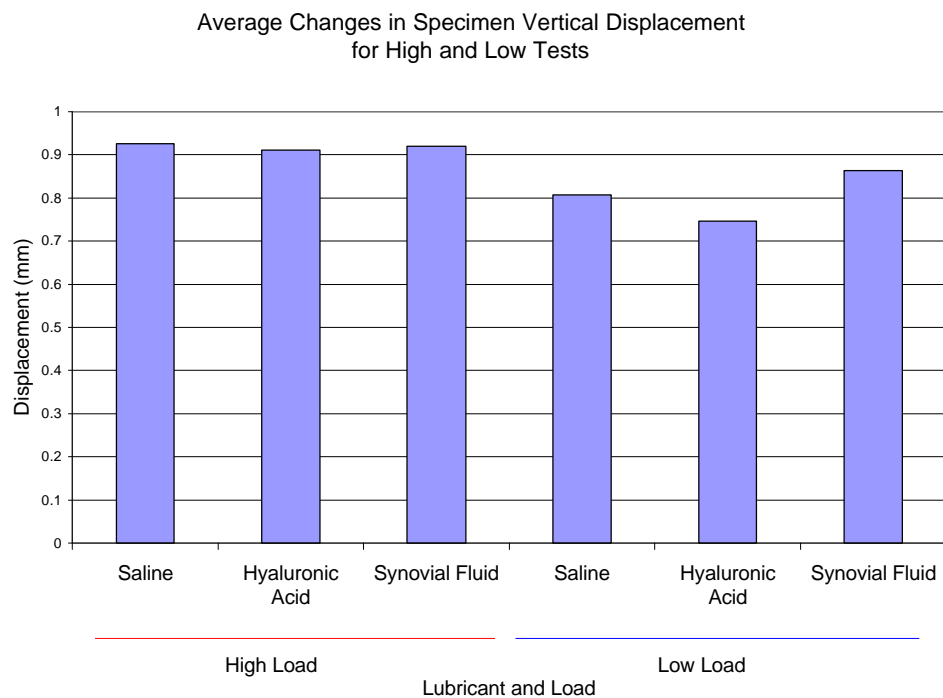
**Figure 5.2: Average Coefficients of Friction at End of Tests**

As shown in these two figures, the differences in friction resulting from different loads are significant. The differences resulting from different lubricants do not show such clear trends. In low load tests, synovial fluid appears to provide higher friction than either saline or synovial fluid, both at the beginning and the end of the test. The differences between lubricants under high loads do not show any trends.

### 5.3 SPECIMEN VERTICAL DISPLACEMENT

An example of vertical displacement data obtained during a test is shown in Figures 4.9 and 4.10. The behavior of the specimen vertical displacement plots did not differ significantly from test to test, under any conditions.

The total displacements for all tests are shown in Section 4.3. It was found that the load was a significant factor for displacement, but the lubricant was not. Figure 5.3 shows the average specimen displacement values for all high and low load tests. No difference among lubricants is visible; the difference between specimen displacements under high and low loads appears as the difference between the heights of the first three and the last three columns in this plot.



**Figure 5.3: Average Changes in Specimen Displacements**

The displacement measured by the LVDT represents a combination of several factors, including wear, elastic deformation, plastic deformation, and time-dependent deformation of the cartilage. A sample calculation was performed to determine, assuming that these displacement changes were caused only by wear, how much wear would be expected through hydroxyproline wear analysis. The calculated cartilage wear values are shown, along with the measured wear values, in Table 5.2.

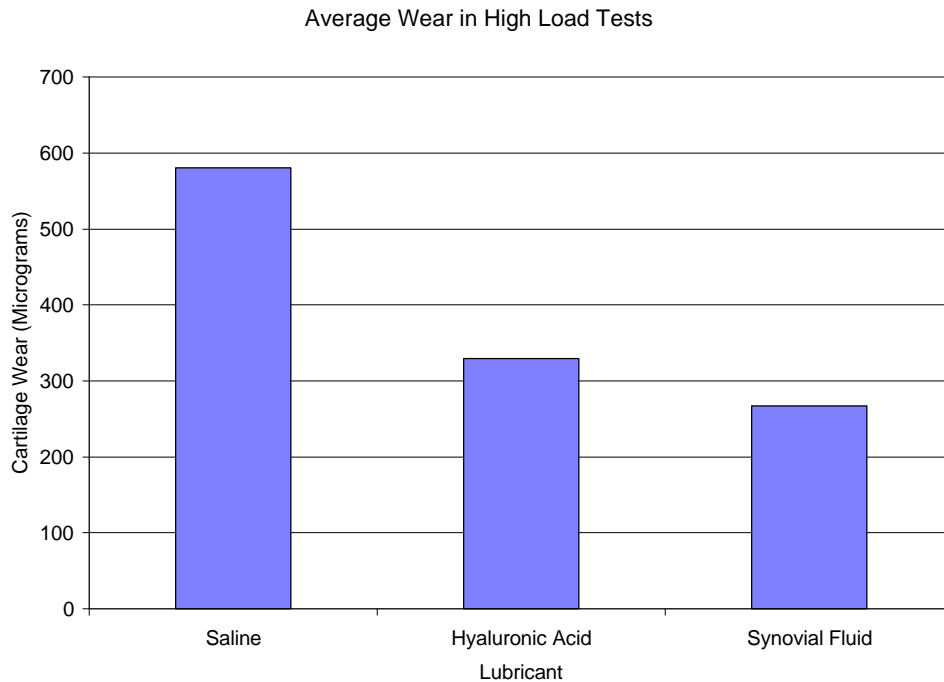
**Table 5.1: Actual and Estimated Wear Values Based On Specimen Displacement Measurements**

Test	Actual Wear, Micrograms of Cartilage	Estimated Wear, Micrograms of Cartilage
1	420	30000
2	610	32800
3	0	23400
4	60	28500
5	1150	29800
6	730	24800
7	0	29100
8	0	22000
9	430	30700
10	0	32600
11	0	27500
12	10	29900
13	610	32300
14	240	25000
15	180	23100
16	170	25000
17	130	25200
18	0	35900
19	90	26600
20	140	21800
21	160	24000
22	220	26100
23	180	23300
24	130	26000

As shown in this table, the estimated wear values based on specimen displacement measurements exceed the actual wear values by an average of more than 250-fold. The specimen displacement values, therefore, reflect large deformations (elastic, plastic, and poroelastic) compared to the dimensional changes caused by cartilage wear.

## 5.4 WEAR

In Section 4.4, it was shown that the lubricant was not a statistically significant factor for wear, while the load was significant. Despite the statistical results, however, a trend can be discerned among the wear values in Figure 4.15. Figure 5.1 shows the average wear values obtained in the twelve high-load (65 N) tests. Saline solution produced the greatest average wear value, 580  $\mu\text{g}$  of cartilage, and synovial fluid produced the smallest wear value, 270  $\mu\text{g}$ . Hyaluronic acid resulted in an intermediate average wear value of 330  $\mu\text{g}$ .



**Figure 5.4: Average Wear Values for Each Lubricant in High-Load Tests**

The trend shown in this figure corresponds to the results obtained previously by Furey [1], for tests in which the same contact pressure (2.1 MPa) was used.

The wear results obtained in this study differ somewhat from those obtained by Furey [1]; although the differences among wear results for the three lubricants follow the trend found by Furey, the relative differences are not as pronounced as in the previous experiments. Several factors may have contributed to this difference in results. As shown in Table 5.1, some of the test variables and aspects of the experimental apparatus used in the present study differed from those used in previous experiments.

**Table 5.2: Test Parameters**

	<b>Furey's Study</b>	<b>Present Study</b>
Contact System:	Bovine cartilage on polished stainless steel	Bovine cartilage on polished stainless steel
Contact Geometry:	Flat-on-flat	Flat-on-flat
Cartilage Specimen Diameter:	5.7 mm	6.35 mm
Applied Load: (High) (Low)	53.4 N	65 N 20 N
Average Pressure: (High) (Low)	2.1 MPa	2.1 MPa 0.63 MPa
Traverse:	6.35 mm	6.5 mm
Sliding Frequency:	40 cycles/minute	40 cycles/minute
Fluid Temperature:	25°C	Ambient (20 - 25°C)
Test Duration:	4 hours	3 hours
Total Cycles:	9600	7200

The difference in the surface finishes of the stainless steel surfaces could have an influence on the friction and wear obtained in the experiments. Differences in applied load, total traverse in each cycle, and test duration may also have had this effect.

## 5.5 SCANNING ELECTRON MICROSCOPY

The images obtained using scanning electron microscopy, shown and described in Section 4.5, provide evidence for differences between the various lubricants tested in this study. All of the high-load cartilage specimens exhibit some sign of wear tracks parallel to the direction of sliding, as well as secondary markings perpendicular to this direction. The degree to which these features appear, however, depends on the lubricant.

The high-load saline test specimen shown in Figures 4.17 through 4.19, possesses deep and pronounced primary wear tracks in the direction of sliding; the smaller secondary markings are clearly visible, and much smaller than the main ridges in the surface. This specimen's features are representative of the typical surface damage obtained using saline solution under high load.

In Figures 4.20 through 4.22, the surface of a high-load synovial fluid test shows a topography that is visibly different from that of the saline specimen. Although the primary ridges are still visible, they are not as prominent on the surface of the synovial fluid specimen. The perpendicular features are much more pronounced, and under high magnification appear to penetrate more deeply into the primary ridges.

In the chart shown in Figure 5.1, the wear produced by hyaluronic acid does not appear much greater than that produced by synovial fluid. The images obtained using SEM, however, show that the damage to these respective surfaces is more significantly different. On the hyaluronic acid specimens, the wear scar parallel to the direction of sliding is the most prominent surface feature. While the secondary features are still visible, they appear more in the form of nodules on the primary ridges than as the perpendicular ridges that were observed on the previous specimens.

The comparison of loads revealed differences among the applied loads that were used. The saline and synovial fluid specimens, shown in Figures 4.26 -4.29 and 4.30 - 4.33, respectively, exhibited pronounced wear tracks in the direction of sliding under both high and low load. The perpendicular wear markings, however, appeared only when the specimens were tested under high load. Under low load, these secondary markings were either faint or completely absent. The hyaluronic acid specimens, however, showed an opposite trend; low-load specimens exhibited wear markings both parallel and perpendicular to the direction of sliding, but high-load cartilage plugs did not have pronounced markings perpendicular to sliding. The primary wear tracks are evident on all specimens. These tracks in the direction of sliding could have been the result of plowing of stainless steel asperities through the cartilage surface; tracks generated by such plowing would deepen upon the removal of load and the recovery of the material. The perpendicular markings, however, are the result of a more complex mechanism of damage. They could be the result of an adhesion between surfaces, which could cause asperities on the cartilage surface to be pulled along with the stainless steel until they are deformed plastically, or they could be caused by a folding and compression of cartilage asperities, squeezing the water from the cartilage matrix in some areas. Whatever the cause of these markings, they do not occur equally at all loads or with all lubricants.



## 5.6 HISTOLOGIC SECTIONS

Sections of the worn cartilage specimens revealed differences among the three lubricants that were not evident from hydroxyproline wear analysis. Histologic sections from saline tests are shown in Figures 4.29 and 4.30, synovial fluid tests in Figures 4.31 through 4.33, and hyaluronic acid tests in Figures 4.34 through 4.37.

The specimens that were lubricated with saline solution exhibit the most pronounced signs of damage. The surfaces of these specimens are extremely rough, especially when compared to those resulting from the other lubricants. Surfaces that were tested with synovial fluid are smooth, with some visible compression of the surfaces. Specimens from hyaluronic acid tests are more severely damaged than the synovial fluid specimens, but the surface ridges on these samples are not as conspicuous as those on the saline specimens.

The damage observed using histologic sectioning corresponds to that which was revealed in the SEM photographs of Sections 4.5 and 5.5. The large ridges visible in Figures 4.29 and 4.30 are cross-sections of the primary wear tracks, parallel to the sliding direction, that are evident in Figures 4.17 through 4.19. The perpendicular features that were observed on the surfaces of most of the test specimens would not appear in histologic sections that were taken perpendicular to the direction of sliding; surfaces containing these secondary features might appear smooth using this observation technique.

Some evidence of the early stages of delamination of the cartilage was found on the surfaces of low-load specimens observed using histologic sectioning. This possible delamination is shown in Figures 4.36 and 4.37. None of the high-load tests showed any evidence of this type of damage. SEM photos of similar low-load specimens showed prominent features perpendicular to the sliding direction, but almost no wear tracks parallel to sliding. This information suggests that the perpendicular markings observed most easily on low-load specimens may be a sign of delamination that occurs just below the surface of the cartilage.

## 5.7 TRANSFERRED FILMS

A difference between synovial fluid and the other two lubricants was discovered through observation of the films that remained on the stainless steel surfaces after testing. While these films were deposited on the surfaces during saline and hyaluronic acid tests, hardly a trace of the films were found on the surfaces of disks tested with synovial fluid as the lubricant.

The presence of these films only on saline and hyaluronic acid tests suggests the possibility that some wear debris may not have been included in the hydroxyproline wear analysis. The small difference between average wear levels in saline and synovial fluid tests may have been underrepresented because of an incomplete collection of material after testing.

Preliminary analysis of these films, as well as fresh synovial fluid and unworn cartilage, has shown that the material on the surface of the stainless steel disks is probably not the same as the unworn cartilage; some chemical change may have occurred during testing. This chemical change could be caused by a degradation of the cartilage under the conditions that were used, or the material found on the surface could be a concentrated collection of a minor constituent of the cartilage. Further analysis of the composition of these films using FTIR and hydroxyproline analysis may provide more information regarding the nature of the transferred or formed material.