CHAPTER 4

RESULTS

4.1 OVERVIEW

The results obtained from this study are divided into five sections. Friction traces from the computer data acquisition system, which provide information about the cycle-to-cycle variations and the transition from static to dynamic friction, are presented first, along with the numerical coefficients of friction. Displacement data measured using the LVDT provide information about the total specimen displacements that were measured during each test, which combine the effects of elastic deformation of the cartilage, plastic (permanent) deformation, poroelastic deformation resulting from the migration of water through the material, and wear. The wear values obtained through hydroxyproline analysis are then discussed, followed by photographs of the surface and subsurface cartilage damage as observed using scanning electron microscopy and histological sectioning and staining. Photomacrographs of the transferred films on some of the polished stainless steel disks will also be presented.

4.2 FRICTION

The friction in this cartilage on stainless steel system was measured using a strain ring attached to the load-bearing shaft, as described in Section 3.1. Friction and load data were obtained steadily throughout the experiment on an analogue chart recorder, and the computer data acquisition system was activated for 3 seconds at intervals during the test. Friction and load data were collected in computer data files after 0, 30, 60, 120, and 180 minutes for graphical display and computation of the coefficients of friction.

4.2.1 CHANGES IN FRICTION DURING TESTS

It was found that the average coefficient of friction increased as the experiment progressed; the value rose rapidly in each case, then settled out to a steady value after approximately the first 60 minutes of each test.

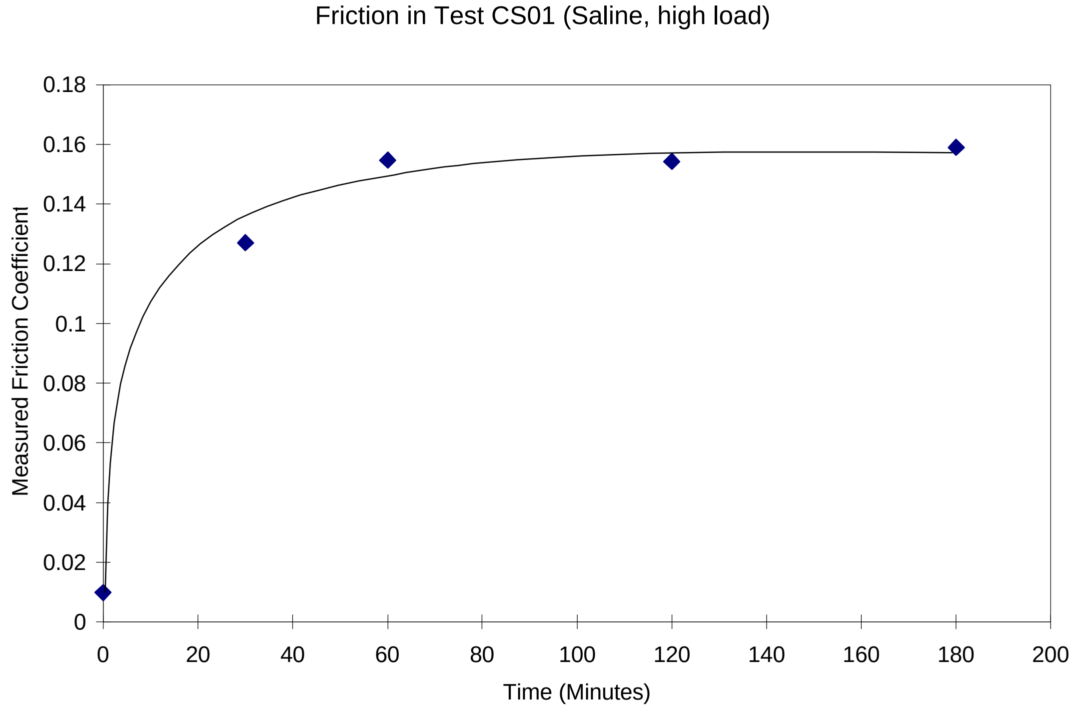

Figure 4.1: Increasing Coefficient of Friction in Saline Test

Figure 4.1 shows a representative plot of the friction coefficient with respect to time in a 3-hour, saline lubricated, high-load test. The friction begins at a value of 0.01, increases rapidly during the first 60 minutes of the test, and remains at about 0.15 for the rest of the test.

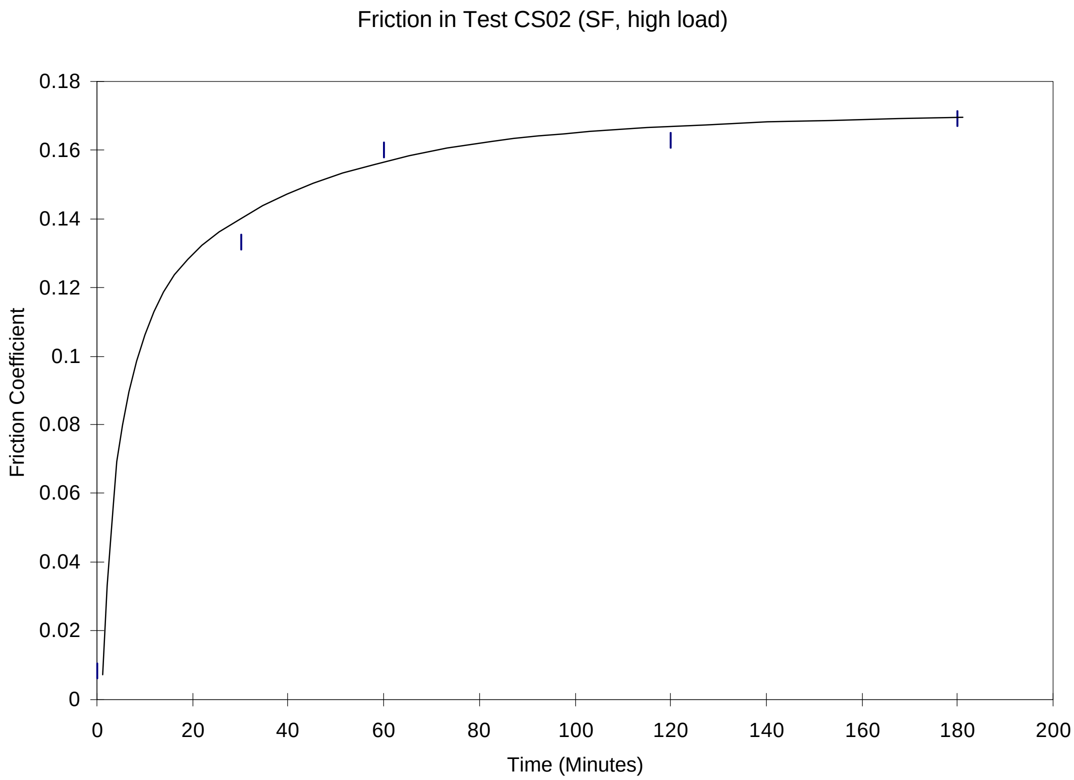

Figure 4.2: Increasing Coefficient of Friction in Synovial Fluid Test

Figure 4.2 shows a similar plot of friction coefficient with respect to time for a synovial fluid test. As with the plot in Figure 4.1, the friction begins with a relatively low friction value (0.008), increases rapidly to about 0.15 after 60 minutes, and remains constant for the remainder of the test.

Another friction plot is shown in Figure 4.3; the data in this figure were obtained during a high load, hyaluronic acid test. As in the other plots, friction rises to a constant value early in the test. Though the actual friction coefficient values differed between the low and high load tests, the friction data followed the same trend with respect to time in all tests.

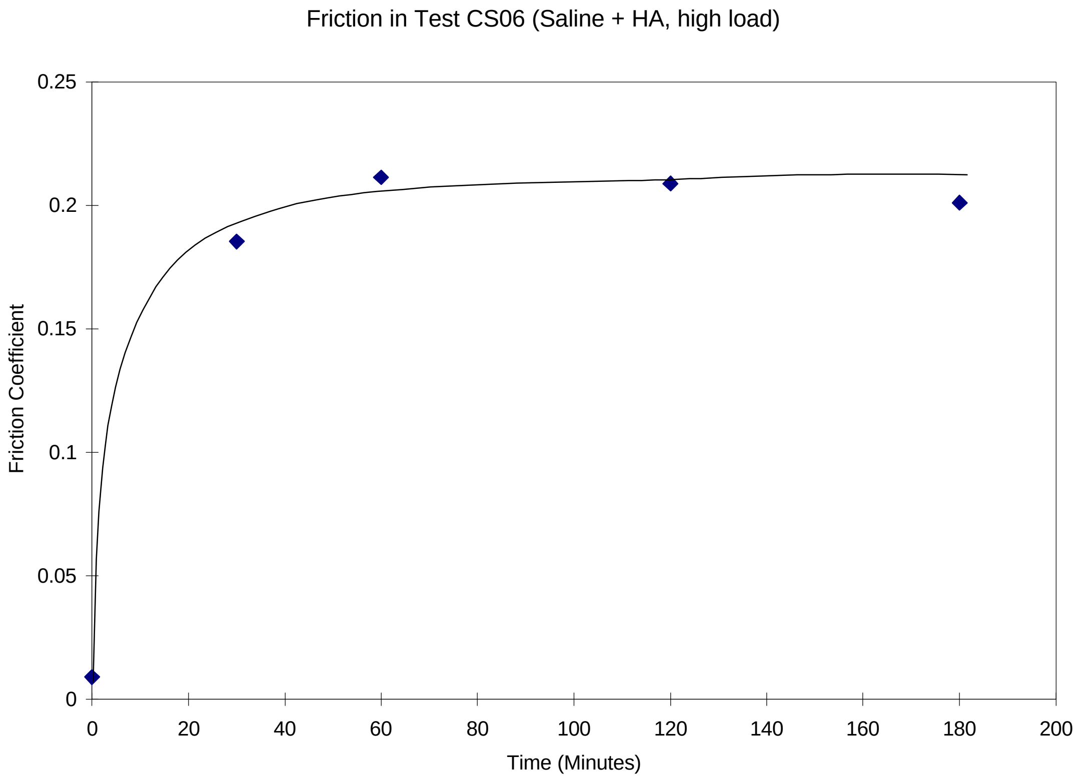

Figure 4.3: Increasing Coefficient of Friction in Hyaluronic Acid Test

4.2.2 EFFECT OF LUBRICANT AND LOAD ON FRICTION

The coefficients of friction at the beginning and end of each test are shown in Figures 4.4 and 4.5. In all tests, the ending friction coefficient is greater than that at the beginning of the test. A complete list of all tests and a summary of test results are provided in Appendix A.

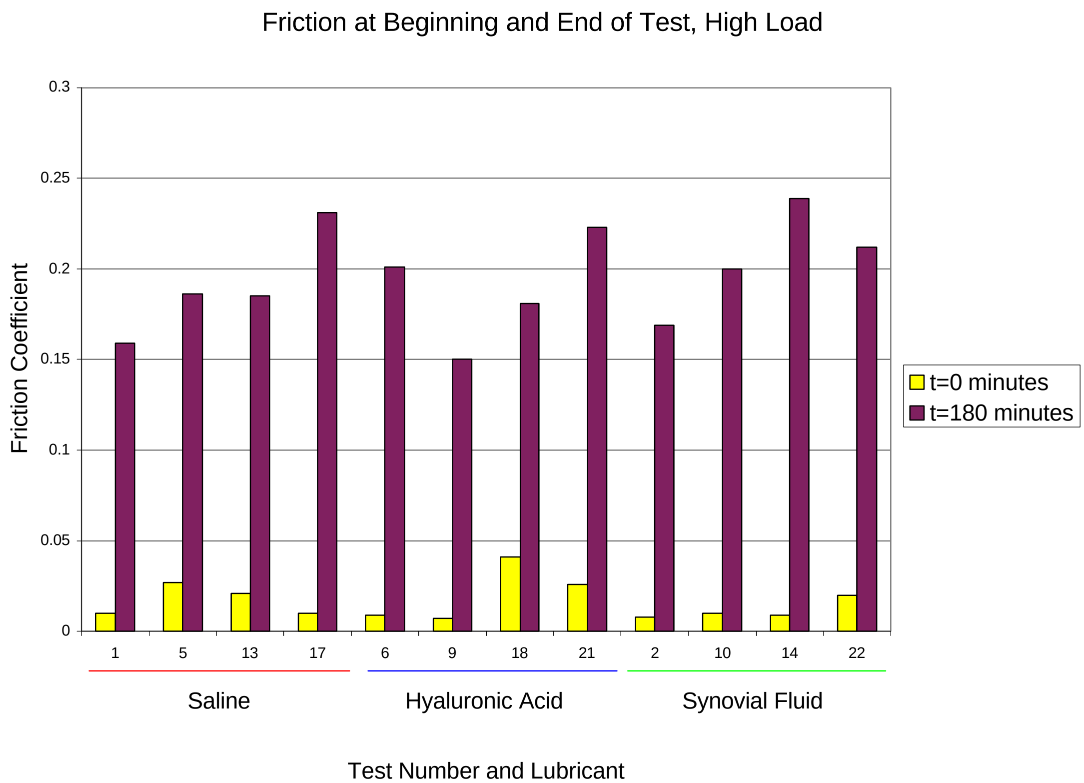

Figure 4.4: Friction in High Load Tests

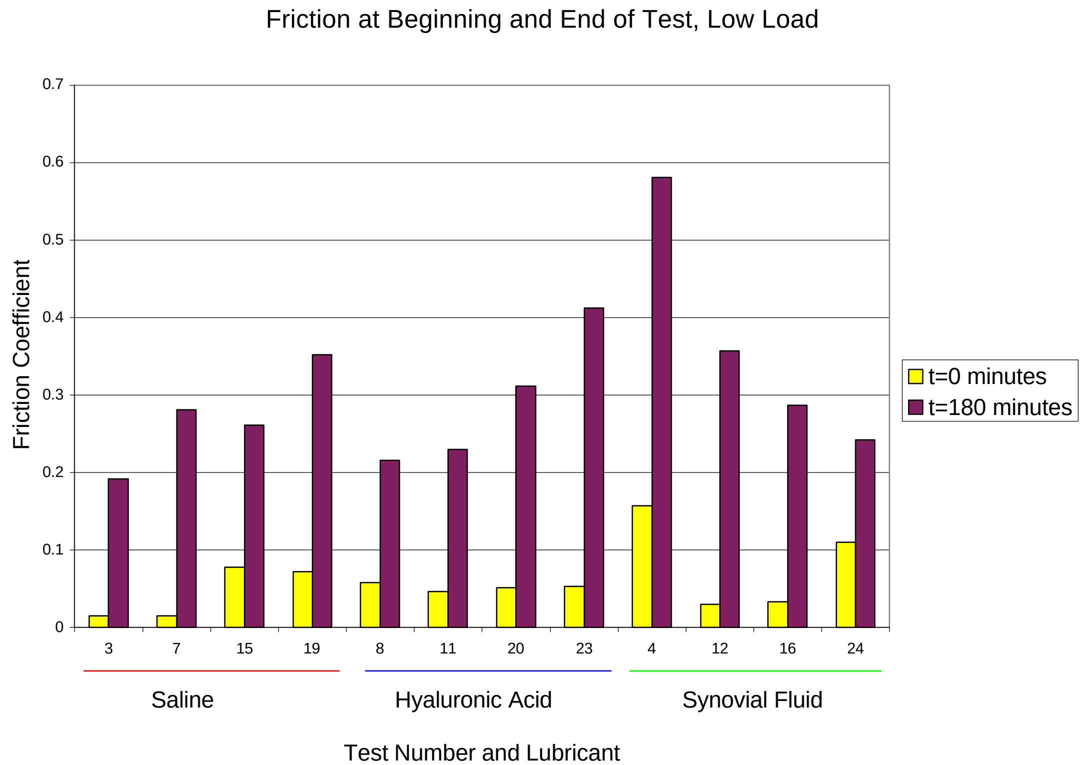

Figure 4.5: Friction in Low Load Tests

The friction data at both the beginning and the end of each test were evaluated using a multi-way analysis of variance to test for significant friction differences from variations in load or lubricant. This analysis is shown in Appendix B. It was determined that the load was a significant factor for friction at the beginning of the test ($p=0.002$), while lubricant and load-lubricant interaction were not significant ($p=0.561$ and $p=0.309$, respectively). Similarly, the analysis showed that, for friction at the end of the test, load was significant ($p=0.002$), and lubricant and load-lubricant interaction were not ($p=0.356$ and $p=0.588$, respectively). It can be concluded from these results, as well as from observation of Figures 4.4 and 4.5, that high-load tests resulted in significantly lower values of friction coefficient than low-load tests, as measured at both at the beginning and at the end of each test. The average friction coefficients are summarized in Tables 4.1 and 4.2.

Table 4.1: Average Friction Coefficients for High Load Tests

	Beginning of Test	End of Test
Saline	0.017	0.190
Hyaluronic Acid	0.021	0.189
Synovial Fluid	0.012	0.205

Table 4.2: Average Friction Coefficients for Low Load Tests

	Beginning of Test	End of Test
Saline	0.045	0.272
Hyaluronic Acid	0.052	0.293
Synovial Fluid	0.083	0.367

4.2.3 SELECTED FRICTION TRACES

Sample plots of friction force and coefficient of friction are shown in Figures 4.6 and 4.7, respectively. In Figure 4.6, the friction force during slightly more than two full cycles of motion is shown; this trace was taken after 180 minutes of sliding under high load (65 N), using buffered saline solution as the lubricant. Positive and negative values indicate the direction of motion. As a cycle begins, the cartilage plug is held stationary by a static friction force. This static friction is indicated by a small spike in the friction trace. After this force is overcome, the friction value drops slightly to its dynamic value. In the example shown here, the dynamic friction force is approximately 15N. The small spike that is visible during the reversal of motion is probably a result of a shifting in the load-bearing shaft as the lower specimen reverses its direction.

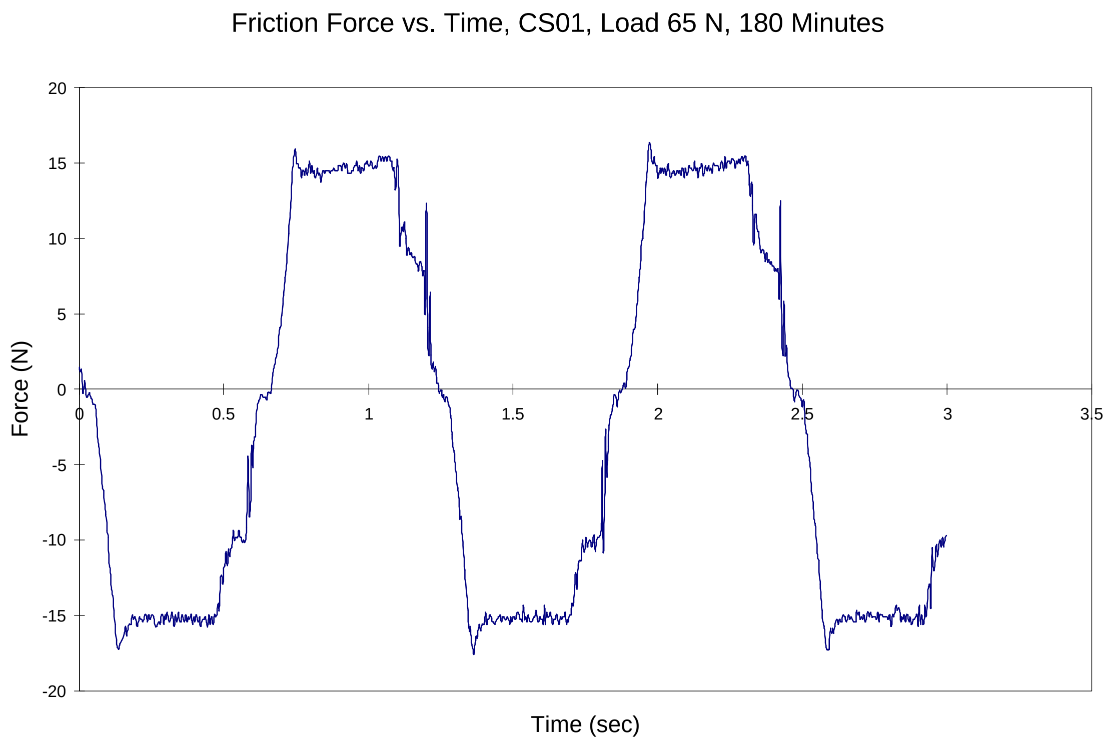

Figure 4.6: Friction Force at End of High-Load Saline Test

Figure 4.7 shows the friction coefficient plot that corresponds to the friction force plot in the previous figure. As in the friction force plot, the conditions of static and dynamic friction can easily be seen as small spikes at the beginning of each half-cycle. Apparent zero values of the friction coefficient are indicative of the reversal of the direction of motion. The shape of the friction coefficient plot did not differ appreciably when different lubricants or loads were used.

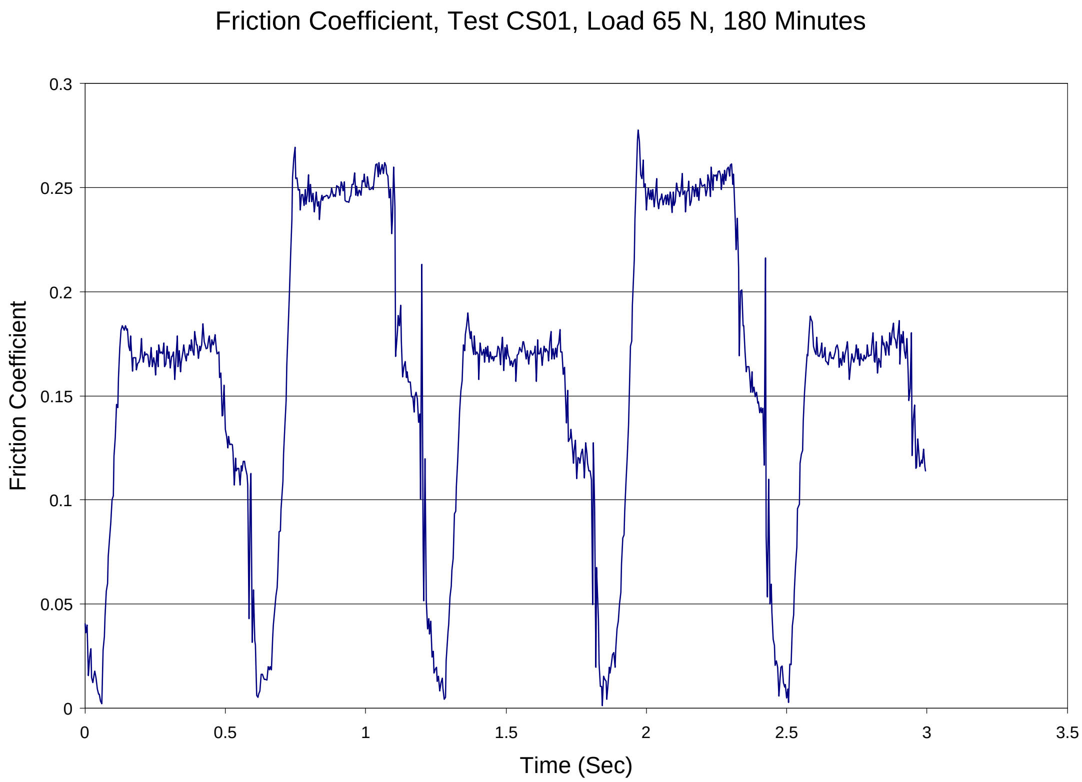

Figure 4.7: Friction Coefficient in High-Load Test

4.3 VERTICAL DISPLACEMENT

The vertical displacement of the shaft, measured by the LVDT, provides two types of information. When analyzed over the course of one or two cycles, the LVDT trace can reveal features of the lower specimen's surface topography. When analyzed from the beginning to the end of a test, the LVDT data shows a total displacement that is comprised of several factors, including elastic deformation, plastic or permanent deformation, time-dependent poroelastic deformation, and wear.

4.3.1 CYCLE-TO-CYCLE DISPLACEMENT MEASUREMENTS

An example of an LVDT vertical displacement trace at the beginning of a high-load test is shown in Figure 4.8. A similar trace at the end of a test (after 180 minutes) is shown in Figure 4.9.

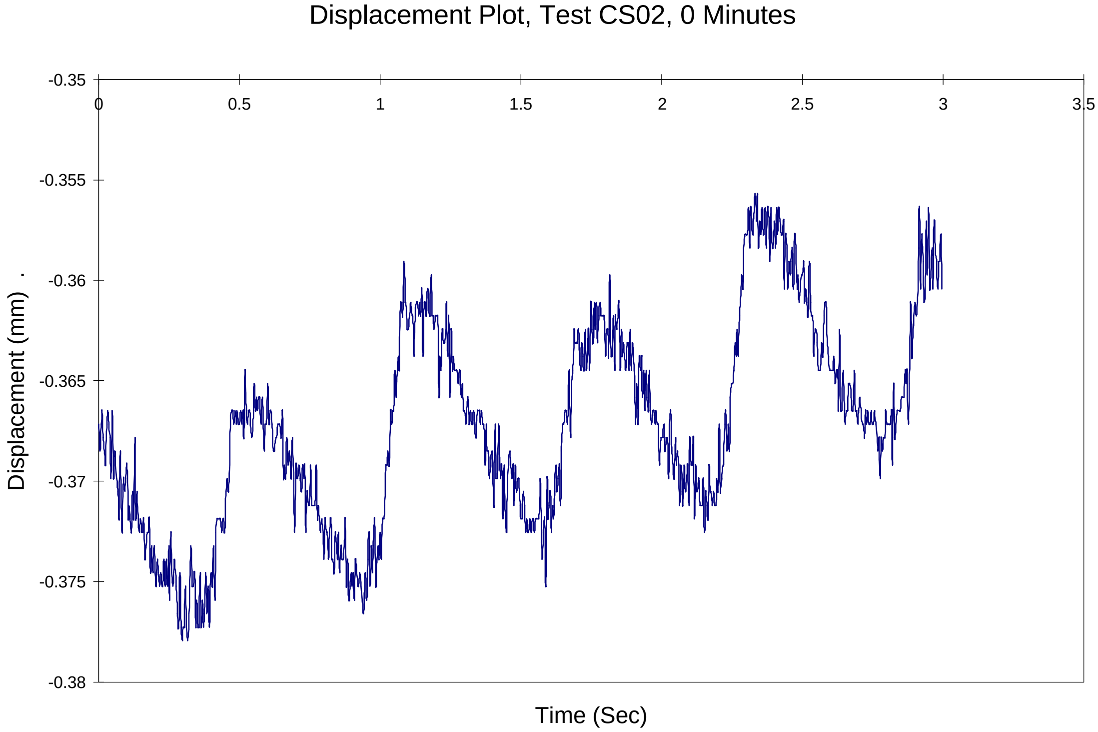

Figure 4.8: Displacement at Beginning of Test, High Load, Saline

In Figure 4.8, the vertical displacement of the upper specimen appears to fluctuate from cycle to cycle as much as 0.01 mm. The cyclic variations in the vertical displacement readings may be attributable to dimensional changes in the cartilage upon reversal of motion. Shear deformation of the cartilage, as well as changes in relative motion during the transition from static to dynamic friction, could cause changes in the vertical displacement values over the course of a single cycle. A portion of the fluctuation may be attributed to the motion of the shaft. The displacement values rise steadily over the three seconds covered by this plot; this change results from the rapid deformation of the cartilage specimen that occurs during the early minutes of the test. The poroelastic deformation of the cartilage, which occurs as water migrates through the material, starts out as a rapid change in the LVDT reading. As the load is applied for a longer period of time, however, this deformation slows to a less noticeable rate. Early plots of LVDT data, therefore, tend to show a rapid displacement change, while later LVDT plots (after 120 or 180 minutes) show no significant displacement aside from the expected cyclic variations.

Figure 4.9 shows a displacement reading obtained from the LVDT during the same test, after 180 minutes of sliding.

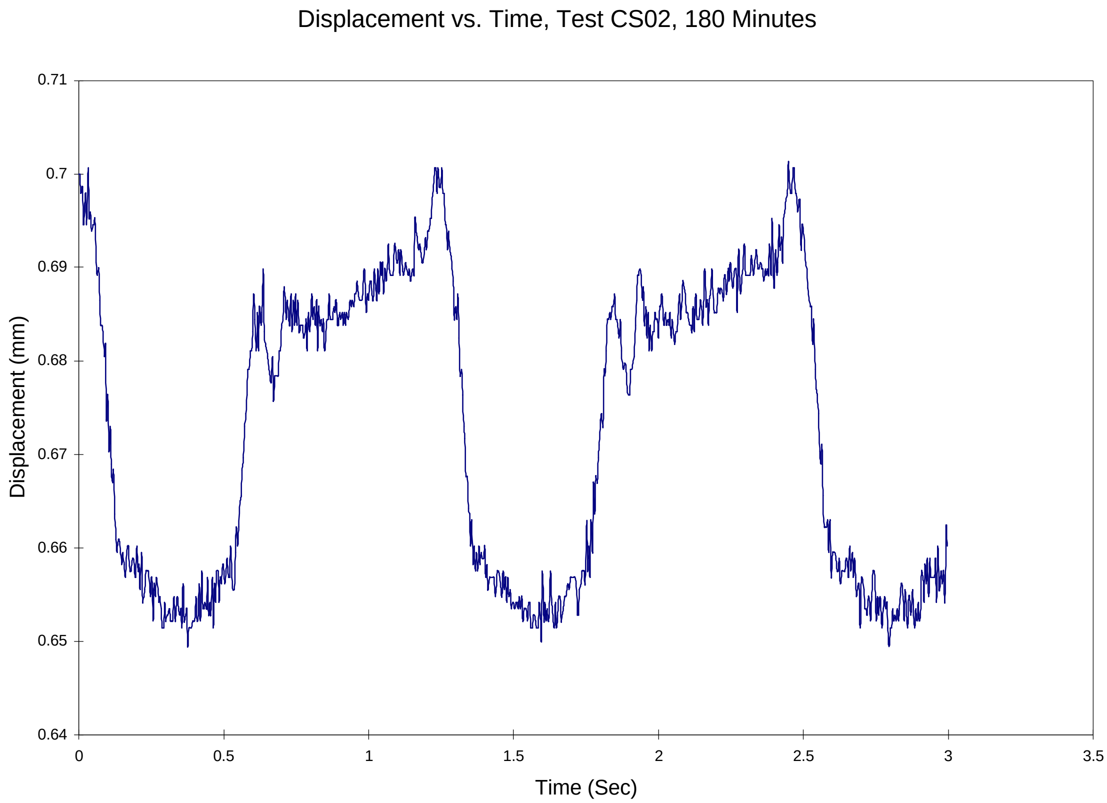

Figure 4.9: Displacement at End of High-Load Test

The plot in Figure 4.9 is considerably different from the earlier trace, primarily because of the lack of gross displacement over the length of the data plot. Because the time-dependent deformation has typically slowed during the three hours of applied load, this deformation is no longer evident over the course of a three-second data capture. Cyclic changes in the displacement reading are still evident, though a different shape than in the earlier plot.

4.3.2 TOTAL DISPLACEMENT MEASUREMENTS

Figures 4.10 and 4.11 show the total displacement for each test; the tests have been categorized by lubricant, which is displayed at the bottom of the figure. Total displacement values were obtained by finding the difference between the average LVDT reading at the beginning and at the end of each test.

The statistical analysis of these data showed that load was a significant factor ($p=0.025$) in determining the total change in vertical deflection of the of the cartilage specimen, while the lubricant and load-lubricant interaction were not significant ($p=0.546$ and $p=0.641$, respectively). The total displacement value was slightly less for low-load tests than for high loads.

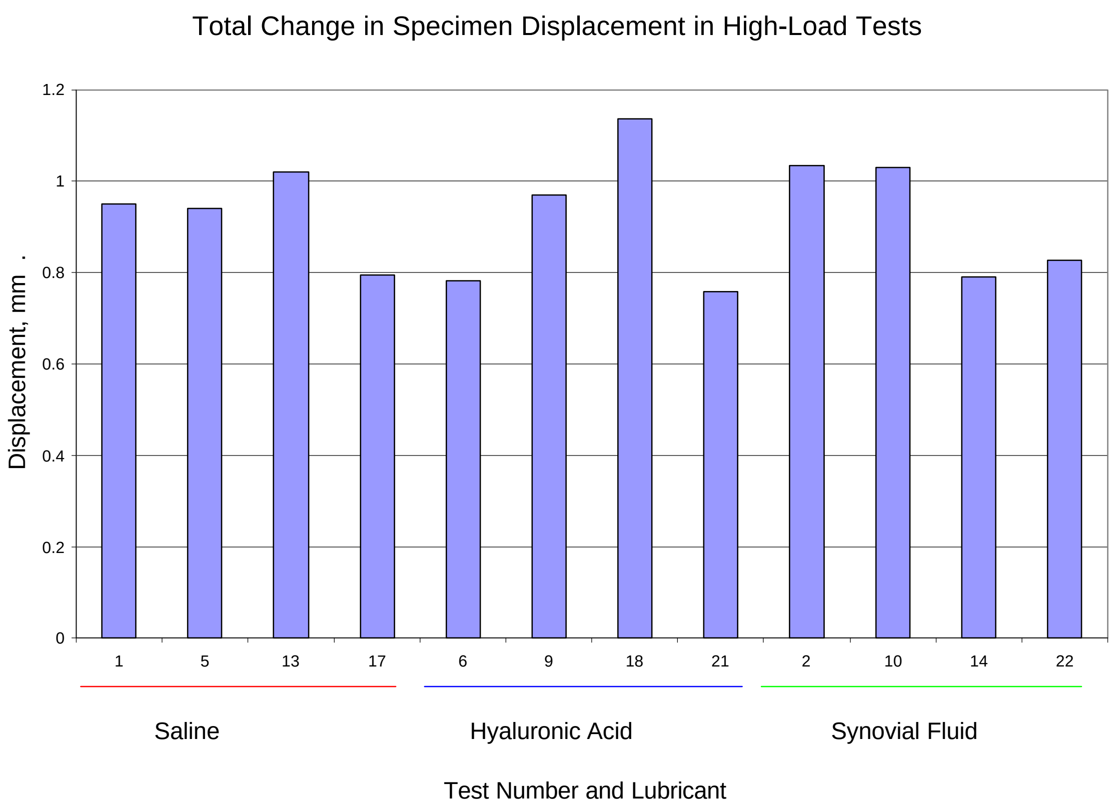

Figure 4.10: Change in Specimen Displacement in High Load Tests

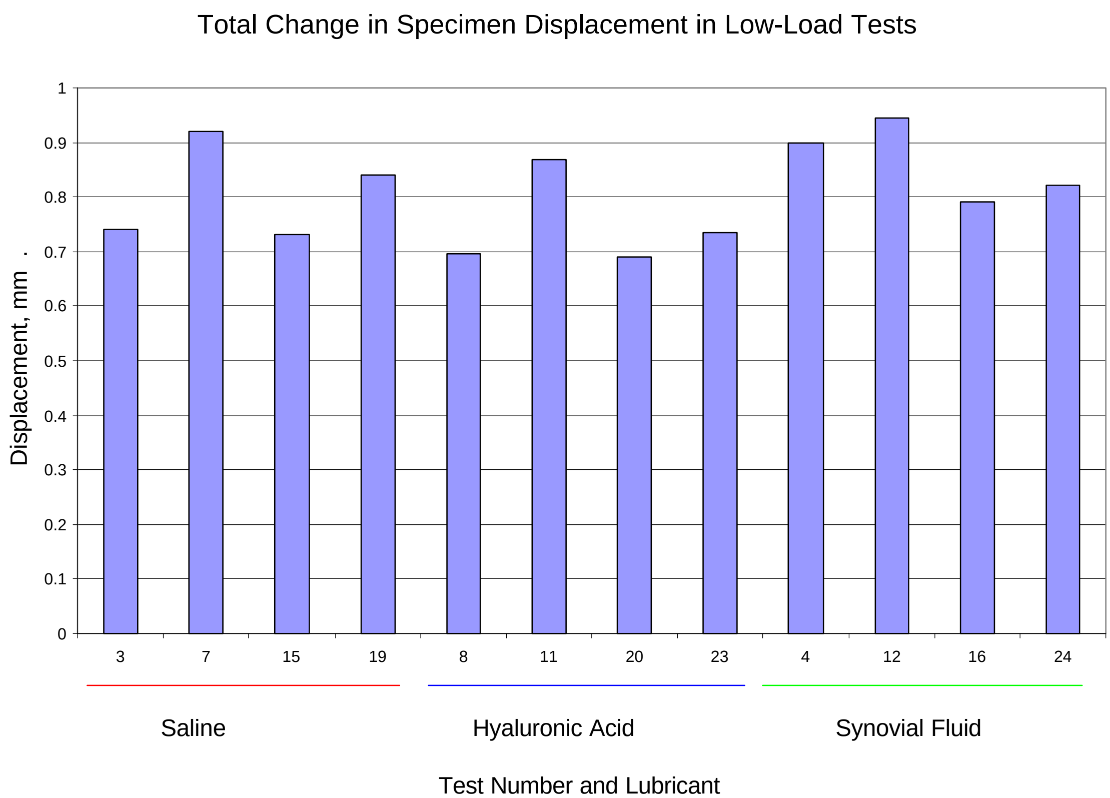

Figure 4.11: Change in Specimen Displacement in Low Load Tests