

Chapter 5

Device Validation and Performance

The final step before actual materials testing was to validate the performance of the designed wear apparatus. Specifically, the motions and forces applied to the bearing substrates (i.e., UHMWPE and CoCr) needed to demonstrate meeting the design specifications established in Chapter 3. As previously mentioned, the primary objective of this project was to develop a multi-station, wear device for the *in vitro* screening and evaluation of currently-available and alternative TKR materials. Although accuracy of the motions and loads were important in reproducing the dynamics of the knee, repeatability in testing was an additional concern. The applied loads and motions can be calibrated and adjusted over time, but over hundreds of thousands of cycles without closed feedback, a slight drift or a skipped step in the motors could lead to erroneous and useless results.

5.1 Motor and Linear Guide Validation (Unloaded)

Although a consideration, consistency of the flexion angle through which the CoCr discs rotated was not as crucial as consistency of the linear guides' sliding distances. Because almost 360° of each disc's surface was suitable for testing (i.e., the only useless portion was where the socket head screw attached the disc to the F/E rod) and current design specification used a flexion angle of only 70°, any drift or skipped steps in the F/E motors should not drastically influence wear results. However, a drift in the linear guides' motors could significantly alter the results. Specifically, if the guides were to drift, wear could begin on a different part of the UHMWPE block, or worse, the CoCr disc could make contact with the stainless steel side of the specimen chamber, damaging the CoCr discs, the tray, and possibly the motors.

To initially ensure this did not happen, a simple test was run without the CoCr and UHMWPE in contact. Using one of the tray's existing socket head screws, a metal ruler was attached to the UHMWPE tray to measure the accuracy and repeatability of the linear guides (Figure 5-1).

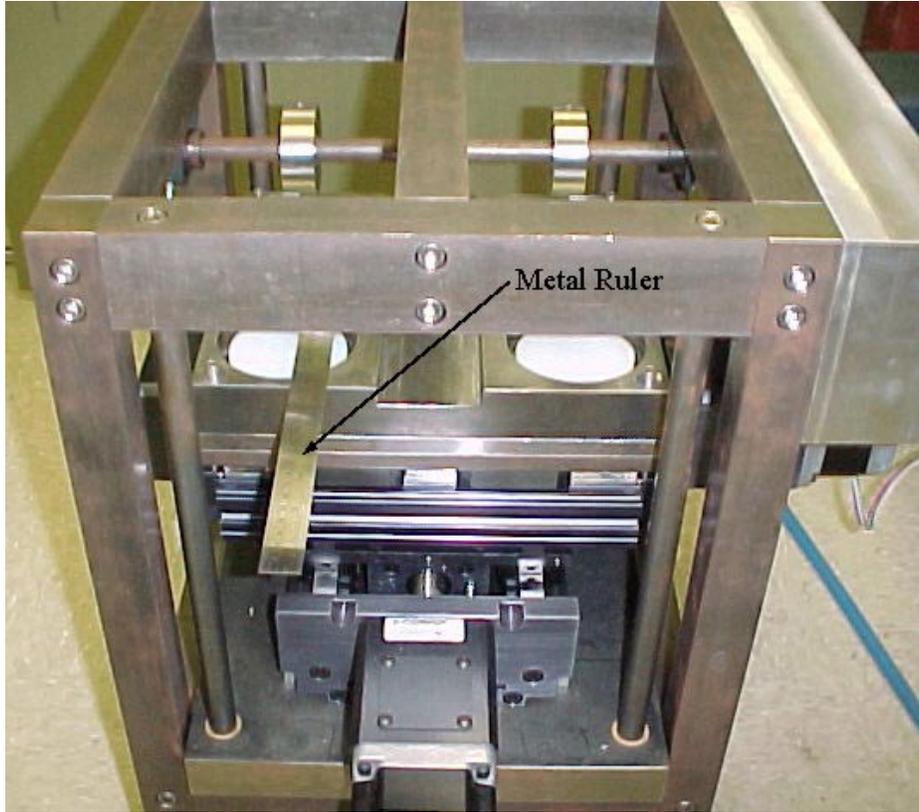


Figure 5-1. Photograph showing the metal ruler used to validate the linear guide motions.

5.1.1 Accuracy Measurement

The device VI discussed in Section 4.4.3 accepted distances for the linear guides in numbers of steps. The motors for the guides had a step size equal to 0.72° . Therefore,

$$\text{One revolution} = 360^\circ / (0.72^\circ \text{ per step}) = 500 \text{ steps.} \quad (5-1)$$

Since every revolution of the motor moved the guide a distance equal to the pitch of the ball screw, or 5 mm (0.20"), the movement of the linear guides should be

$$\frac{500 \text{ steps}}{\text{revolution}} \cdot \frac{\text{revolution}}{5 \text{ mm of movement}} = 100 \text{ steps per mm.} \quad (5-2)$$

To experimentally check the accuracy of this result, the metal ruler was aligned in the direction of AP sliding (Figure 5-1), and numerous inputs were made to the VI. If the

motors, drivers, and computer software were functioning properly, every 100-step input would result in one mm of guide movement. A T-square securely fastened at the edge of the frame measured the original mark of 80.5 mm on the ruler. An input of 1000 steps from the PC moved the guide, and its new position was measured as 70.5 mm on the ruler. The 10 mm of movement for 1000 steps of input was exactly as expected. Measurements were taken at various other positions in various increments, and each measurement confirmed that 100 steps of input resulted in one mm of AP sliding. A similar accuracy test for the cross shear guide confirmed that the motors were functioning properly and were not skipping any steps during unloaded operation. These steps were later repeated during loaded operation (refer to section 5.3).

5.1.2 Repeatability Measurement

The T-square was also used to check the repeatability of the linear guides. The start position was again confirmed to be 80.5 mm on the ruler. The motor then repeatedly ran through the double-humped AP sliding curve with peaks at 5 and 10 mm. Every 500 cycles, testing was paused and the start position was measured. Through 10,000 cycles, the start position of 80.5 mm never varied, validating the repeatability of the motor during unloaded operation.

5.2 Validating the Applied Force

Determining the exact force at the CoCr / UHMWPE interface was the most difficult aspect of the validation process. Without a load cell available, crude estimations were used to predict the applied load. The first step in validation was to test the pneumatic valve to ensure it was providing the expected pressures. Knowing the bore size of the cylinder, the weight of the parts it was lifting, and assuming the pressures in the cylinder were accurate, reasonable approximations of the applied force were determined.

5.2.1 Validation of the Valve

To measure the valve's accuracy, a pressure gauge (W.W. Grainger) was connected to the output hose of the valve. A VI was written in LabView™ to accept a desired output pressure and inlet valve pressure, which would output the corresponding binary number to the backplane and the valve. Then, the gauge's reading was compared to the desired pressure and the truth table of Figure 4-13.

Unfortunately, the two pressure gauges, the one used to adjust the inlet pressure and the one reading the output pressure, were inaccurate from the beginning (refer to Appendix C). A calibration factor was used to equate the readings of the two gauges, and the valve appeared to be working properly. Appendix C includes table C-1 showing the various inlet and desired pressures tested.

5.2.2 Estimation of the Cylinder Force

Even without the use of strain gages or a load cell, the force applied by the cylinder can be estimated by knowing its bore size and the pressures in its two ends. For instance, suppose the cap end of the 5" bore cylinder was pressurized at 90 psi, and the valve was supplying air at 60 psi to the rod end. The net pressure, P_N , in the cylinder would be 30 psi and the total force, F_T , would be found as follows:

$$F_T = \frac{\pi}{4} D^2 P_N = \frac{\pi}{4} (5 \text{ in})^2 (30 \text{ psi}) = 589 \text{ lbf} \quad (5-3)$$

where D is the diameter of the cylinder.

Since the cylinder must combat the weight of the table support, the two linear guides, the tray support, tray spacer, and the stainless steel tray, F_T is not the force at the material interface. The total weight of the lifted parts was estimated to be 250 pounds (refer to Appendix G). By subtracting that weight from the total force, the force at the material interface should be 339 pounds at a net cylinder pressure of 30 psi. After repeating these calculations for other input pressures, a table of estimated forces was devised (Table 5-1).

Table 5-1. Estimated loads experienced by the device and each station for increasing cylinder pressure.

Net Cylinder Pressure (psi)	Cylinder Force (lbf)	Total Interface Force (lbf)	Interface Force per Station (lbf)
0	0.0	0.0	0.0
10	196.3	0.0	0.0
20	392.7	142.7	35.7
30	589.0	339.0	84.8
40	785.4	535.4	133.8
50	981.7	731.7	182.9
60	1178.1	928.1	232.0
70	1374.4	1124.4	281.1
80	1570.8	1320.8	330.2
90	1767.1	1517.1	379.3
100	1963.5	1713.5	428.4

5.2.3 Strain Gage Calibration

Although the previous calculations should give an accurate estimate of the force between the CoCr and the UHMWPE, the actual forces at various pressures were still unknown. To better estimate the actual force, a single 350-ohm strain gage was mounted in the center of the upper surface of the top middle bar, parallel with its long axis.

Before using known weights for calibration, a check of the gage's linearity was necessary. Pressures were applied to the cylinder in increments of 10 psi, and the gage's reading in microstrain (μs) recorded by a strain indicator (P-3500, Measurements Group, Raleigh, NC) for each applied pressure. Even though only minimal amounts of strain were attainable, the linearity of the gage was excellent, at less than 1% of full scale. The strain measurement was repeated for each of the pressures to ensure linearity and repeatability of the gage. Data from the original strain gage calibration is given in Appendix D. The linearity of the recorded data points is shown in Figure 5-2.

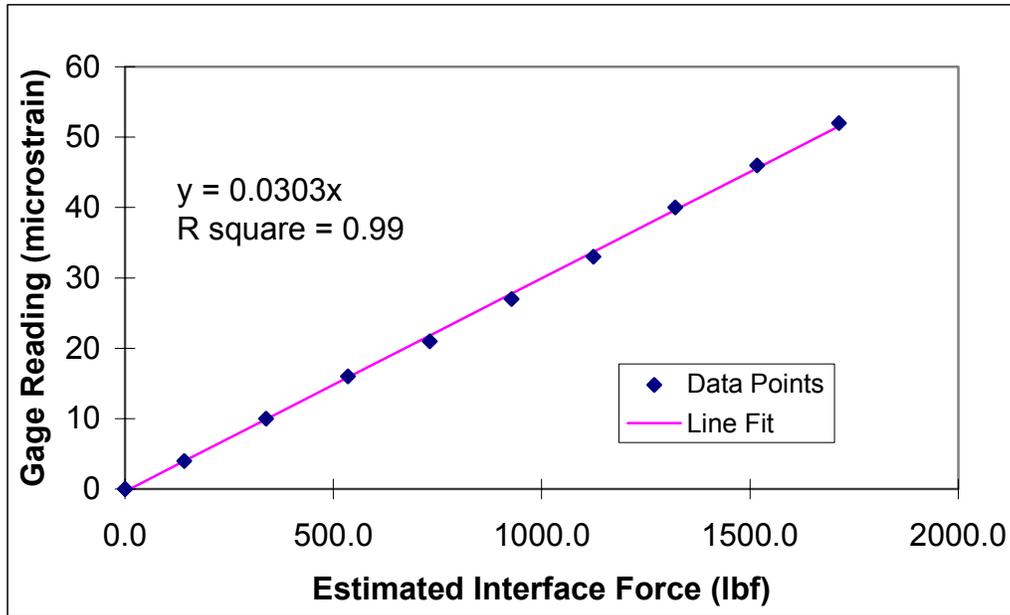


Figure 5-2. Plot of the recorded strains at various cylinder pressures, illustrating the linearity of the strain gage. The cylinder pressures were converted to the estimated interface forces of Table 5-1, because the cylinder required a minimum of 15 psi to lift the UHMWPE in contact with the CoCr.

As seen in Figure 5-2, the recorded strains were quite small. Only 52 microstrain were recorded at the maximum interface force of over 1700 pounds. Despite this lack of strain, calibration with known weights continued as planned.

Scrap steel from the ESM machine shop was weighed, and then uniformly placed atop the four CoCr discs. The total weight and strain gage reading were recorded after the addition of each piece of steel. With all the scrap metal piled on, approximately 200 pounds, the strain indicator box read only 6.5 μ s. Several students of varying weight were then recruited to stand atop the piled steel to obtain more data points and increase the total weight. The maximum calibration weight peaked at 395 pounds, yielding 13 μ s. The collection of data points and line fit for the applied weight is shown in Figure 5-3. Table D-2 of Appendix lists the data points from the known weight calibration.

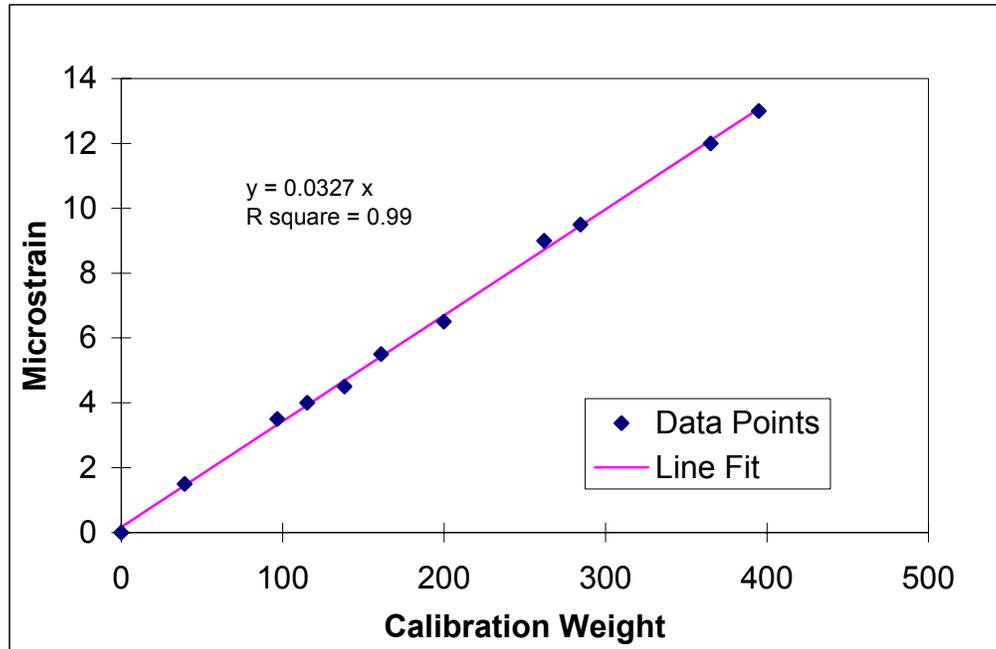


Figure 5-3. Plot of the resulting strain for each of the known weights. The strain gage behaved linearly.

With the strain gage's linearity using known weight under 400 pounds, and its linearity under the high forces of the pneumatic cylinder, it was possible to reasonably predict the strain at higher weights, as if more scrap steel were used. By extending the line fit of Figure 5-3, the strains using the known weight and the strains from the cylinder test were compared (Figure 5-4).

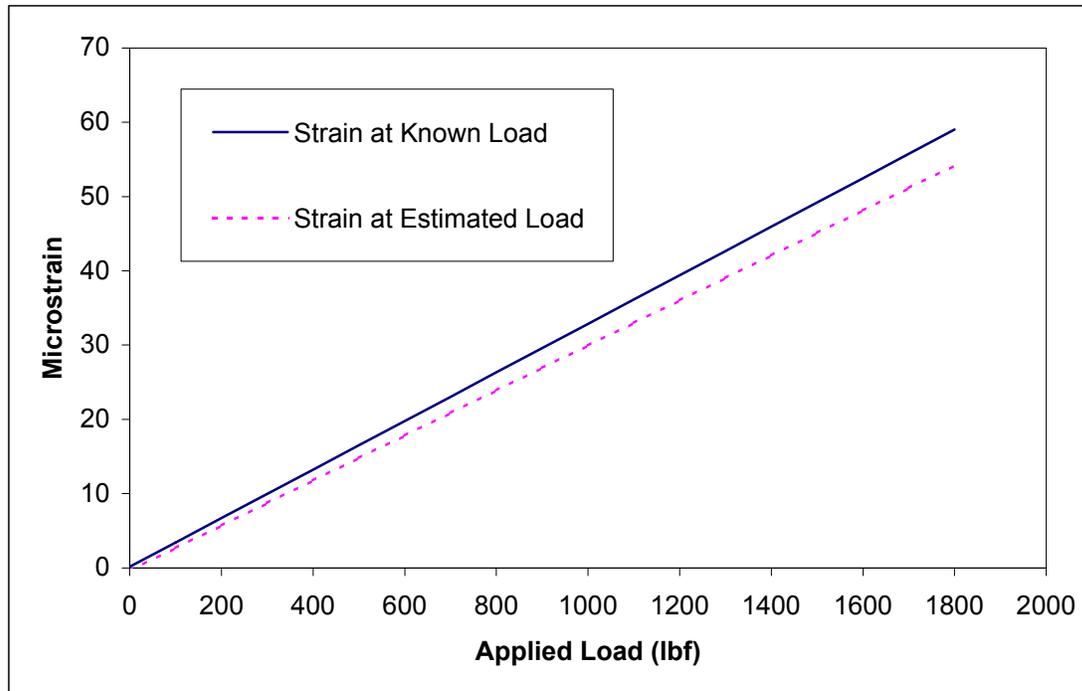


Figure 5-4. The strains at the predicted interface forces (line fit from Figure 5-2) and the strains from the known applied loads (extrapolated line fit from Figure 5-3) plotted together.

As demonstrated in Figure 5-4, the strain output from the predicted and known loads does not vary greatly. For instance, known and estimated cylinder forces of 1300 pounds yielded strains of 42.7 and 39.0 μs , respectively, a difference of only 8.5 percent. Since the two curves are linear, increasing the net cylinder pressure 8.5% should provide the desired interface force. A comprehensive analysis of the errors in the pressure gauge, strain gage, weight measurement, and uneven loading, might conclude that the two curves presumably lie within overlapping ranges of error, but this was not done. Speculatively, an error analysis would show that the estimated interface forces of Table 5-1 are, in all likelihood, very similar to the actual forces at the material interface, and could be deemed adequate for use during testing.

5.2.4 Loading Dynamics

The last aspect of the loading to consider was the dynamics and synergy of the system in its entirety, from the PC output and backplane to the valve and cylinder. The valve's frequency response was discussed briefly in Section 4.4.1. Unfortunately, the actual frequency response of the cylinder is not known and cannot be evaluated without

the use of a real-time load cell. Although the strain gage was suitable for static load tests, it was not interfaced with the PC for dynamic measurement. The large bore of the cylinder will take some time to fill after each pressure change of the valve. As previously discussed, this predicted lag in the system may “smooth” the steps of the binary valve, but without a load cell, this assumption cannot be confirmed. The lack of dynamic loading validation is discussed further in the Recommendations section of Chapter 6.

5.3 Initial Preliminary Tests

Before using the wear test apparatus for actual TKR materials testing, preliminary tests were needed to ensure that the device was operating properly under actual test conditions, including physiologically-correct loading with AP sliding, F/E, and a bovine serum lubricant. Thirty milliliters of bovine serum (Hyclone Laboratories, Logan, UT) was poured into each of the four specimen chambers. A standard operating procedure was developed and utilized in this preliminary testing (refer to Appendix E). Initial tests were performed using AP sliding, F/E, and the Seireg loading curve. Once completed, constant-load tests using the bow-tie pattern of Figure 4-16 were also run to examine the device under cross-shear. In all, the machine went through hundreds of random tests, varying in length from 100 to 15,000 cycles, to subjectively observe the device's performance.

Measurements for repeatability and sliding accuracy were repeated for the loaded case, and a subjective examination of device performance was conducted during testing. Repeatability and accuracy performance of the motors were identical to those reported in the unloaded case. However, it was noted, that the linear guide motor occasionally hit its stall torque towards the large peak of the AP sliding curve. Adding minimal amounts of bovine lubricant a couple of times a day seemed to eliminate this problem. The preliminary tests dispelled any concerns of frame vibration, although noise from the pneumatic valve was annoying. The addition of a second muffler should assist in further noise reduction of the valve. A box fan was added to maintain the F/E motors at a stable operating temperature. Overall, the preliminary tests were successful, and the device was deemed ready and capable of TKR materials testing.

5.4 Preliminary Test of UHMWPE and CoCr

Although the examination of different modes of UHMWPE wear, and the comparison of wear rates and mechanisms of several TKR materials was beyond the scope of this project, a brief test was performed to subjectively observe the designed device's ability to initiate wear of UHMWPE. The preliminary test with bovine serum lubricant ran for 50,000 cycles, alternating every 5,000 cycles between AP sliding with the Seireg loading curve at a maximum load of 430 pounds per station, and the bow-tie cross shearing with a constant load of 280 pounds per station. The testing procedure was chosen to include the types and degrees of loading and motion under which the device would typically operate. At the completion of the test, the UHMWPE (HSS, PolyHi Solidur, Fort Wayne, IN) blocks were removed, rinsed, and visually inspected for wear.

Upon gross examination, the wear of the UHMWPE surface appeared as a smooth, shiny rectangle (Figure 5-5), similar to that described by Blunn *et al.* (1991) concerning the results of their rolling test. Although this wear was noticed after what is considered to be equivalent to three weeks of average walking, it should be noted that the CoCr discs were unpolished, undoubtedly increasing wear. While the result of this initial test should in not be used to predict TKR wear, it clearly showed that the device was capable of initiating a wear track in the UHMWPE.



Figure 5-5. The worn UHMWPE block after 50,000 cycles of testing. The wear track can be seen as a shiny rectangle on the material's surface.

Although more stringent validation methods, such as load cell calibration and closed feedback optical sensors, could have been used, the device performed well under the methods that were available in the laboratory. Through simple measurement, loaded and unloaded strain gage calibration, and preliminary wear tests, the device proved effective at reproducing the desired motions and loads, and initiating wear.