Testing of Compliance in a Prosthetic Socket Fabricated Using Selective Laser Sintering

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ABSTRACT

Solid freeform fabrication techniques offer potential as manufacturing technologies in applications that require custom design. One such application is the fabrication of prosthetic sockets. This paper reports on research to manufacture compliant below-the-knee prosthetic sockets using selective laser sintering (SLS). Compliance in the socket is a critical factor in the level of comfort the amputee experiences during gait. The ability to control local geometry is seen as an advantage of SLS in fabricating compliant sockets. This paper presents work on developing a model of compliance for sockets constructed of Duraform®. The approach taken here is to provide the necessary compliance by controlling the wall thickness of the socket. To select the right thickness, a study of the wall deflection with respect to contact pressure was performed. An experimental testing device was designed and constructed to test the deflection versus pressure for different thicknesses of test circular discs made of Duraform®. The results were correlated to a finite element model. These results will be used for designing the compliance in the walls of prosthetic sockets fitted to actual patients.

INTRODUCTION

This paper presents results from the on going research to manufacture a compliant transtibial (below-the-knee) prosthetic socket using Selective Laser Sintering (SLS) [Rogers, et al., 1991; Stephens, 1999; Stephens et al. 2000]. This approach has several potential advantages over conventional methods, such as easy duplication of sockets, flexible geometric design and better control on the socket thickness. In particular, SLS offers the potential to increase compliance in the socket in selected locations by controlling the local geometry. Increased compliance relieves excessive pressure on the residual limb tissue, especially in the sensitive bony areas, thereby enhancing the comfort level experienced by the amputee. A socket produced by SLS is shown in Figure 1. The goal of the current research is to develop a model of the compliance of a SLS material. This model will be used to design sockets based on customer needs and feedback from a prosthetist.

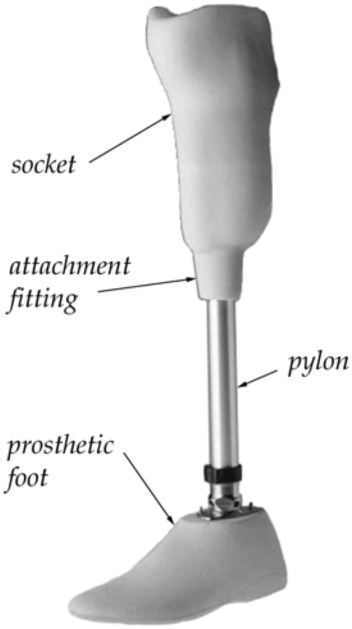


Figure 1. SLS fabricated transtibial socket.

In the present work, a series of experiments was conducted to study the compliance of thin Duraform® discs processed using SFF. The experiments were then used to verify a finite element model of the compliant discs. In this paper we describe the experimental setup and the results obtained from pressure tests on the discs. We then compare the results to finite element simulations of the loaded discs.

PRESSURE-DEFLECTION EXPERIMENTS

The test apparatus is designed to simulate as closely as possible the load conditions on the compliant region of the socket. The design assumes the pressure on the compliant region is uniform. To simulate this, thin compliant discs, such as those shown in Figure 2, were fabricated from Duraform® and subjected to air pressure. The circular disks vary in thickness, being thicker toward the outer diameter and thinner in the middle. The thin middle section has a nominal diameter of two inches. Discs with inner thicknesses ranging from 0.033" to 0.05" were fabricated. Each disc has a diameter-to-thickness ratio of 20, permitting a thin disc assumption for analysis. The discs were subjected to pressures ranging from 0 to 60 psi.

Figure 2. Duraform® specimens.

Experimental Apparatus

A photograph of the test device is shown in Figure 3. The inner diameter of the aluminum cylinder is two inches, corresponding to the thin region of the specimens. Since the Duraform discs were porous and not airtight, a very thin plastic sheet was used to seal the air pressure. Two soft rubber gaskets are also used to make the seal between the support discs airtight. One circular flange is attached to the main cylinder using metal-to-metal glue. The other flange is used to clamp the Duraform disc, which is centrally placed between the flanges and held rigidly on its periphery with four ¼ inch nuts and bolts. Compressed air is supplied using a Schrader valve that is screwed into the other end of the cylinder as shown in Figure 4. It is important to note that this device was designed for static load analysis. The instruments used to measure pressures and deflections were a pressure gauge and a dial gauge. The pressure gauge is attached to a half-inch pipe nipple that is screwed into the side of the cylinder. The resolution of the pressure gauge is 5 psi for the range 0-20 psi, and 4 psi for pressures above 20 psi. The resolution of the dial gauge is 0.001". These were found to be reasonably accurate for these experiments. To avoid disturbance in the dial gauge readings the whole device is rigidly clamped to the table as shown in Figures 4 and 5, with the probe of the dial gauge adjusted so that it touches the center of the disc. The set up can be seen in Figure 5. The maximum pressure of the compressed air supply was 100 psi.

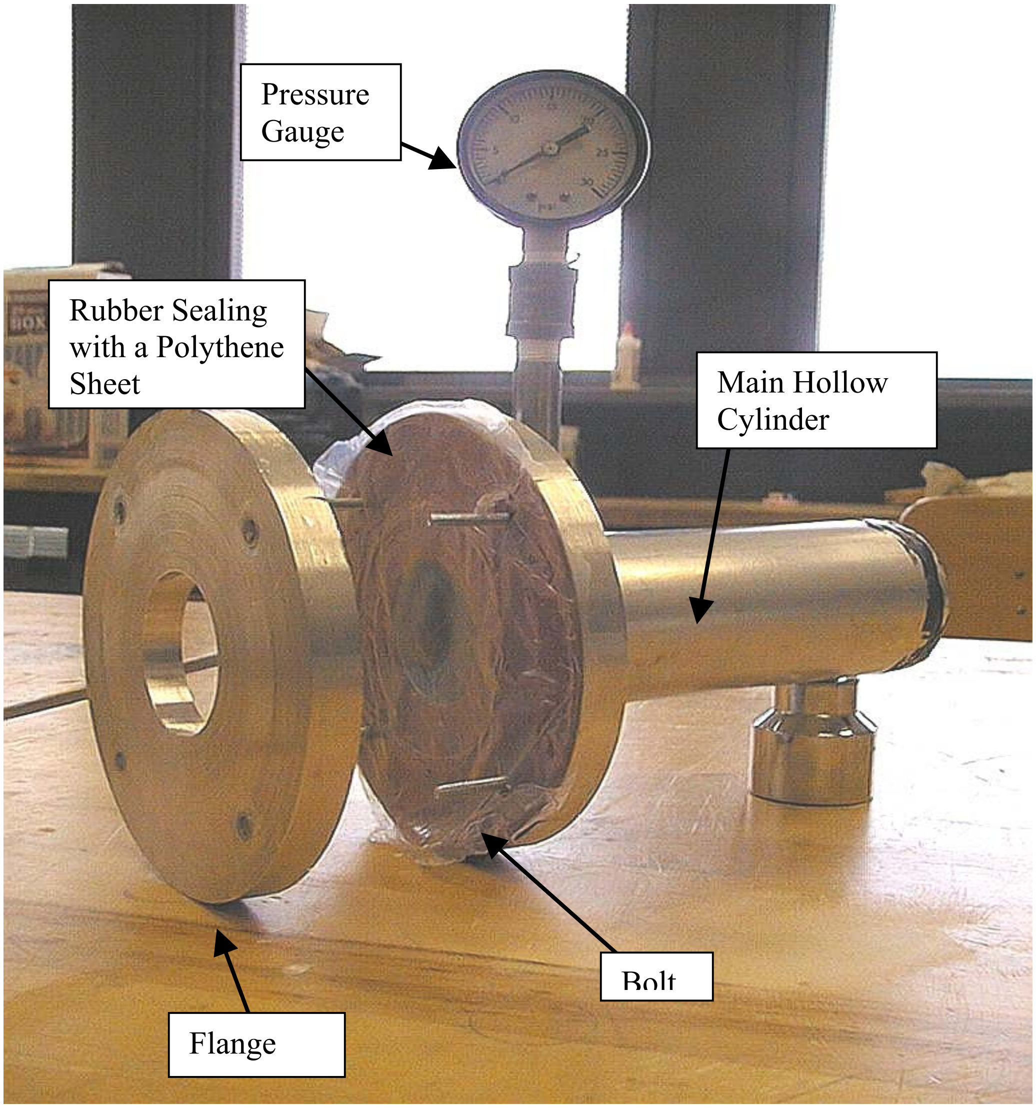


Figure 3. Device used to test compliance.


Figure 4. Experimental set up (back view).

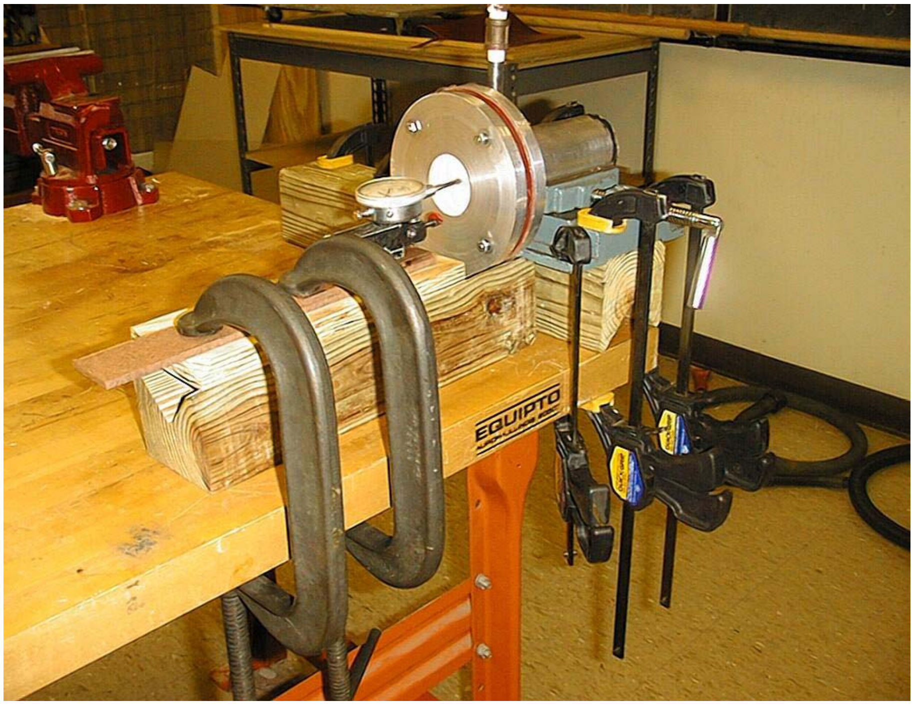


Figure 5. Experimental set up (front view).

Experimental Results

The Duraform discs of varying thicknesses (0.033”-0.05”) were made using a Sinterstation 2000. The first set of discs made was of recycled powder. A subsequent set made from virgin powder was tested. As the differences were negligible, we present the results from the recycled powder. Air pressure up to 60 psi was applied to the Duraform, then decreased in steps as the deflection at the center of the disc was recorded. Three sets of readings were taken for each disc. Figure 6 shows the results for the 0.5” disc, and Figure 7 shows the results for the 0.033” disc.

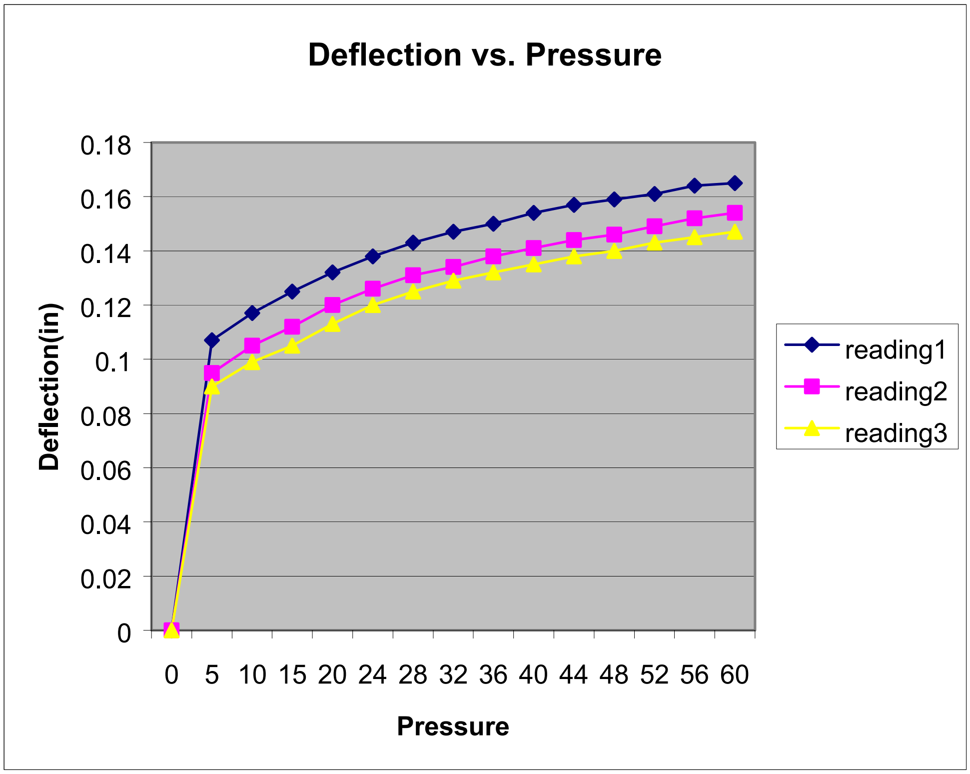


Figure 6. Deflection results for 0.05” disc.

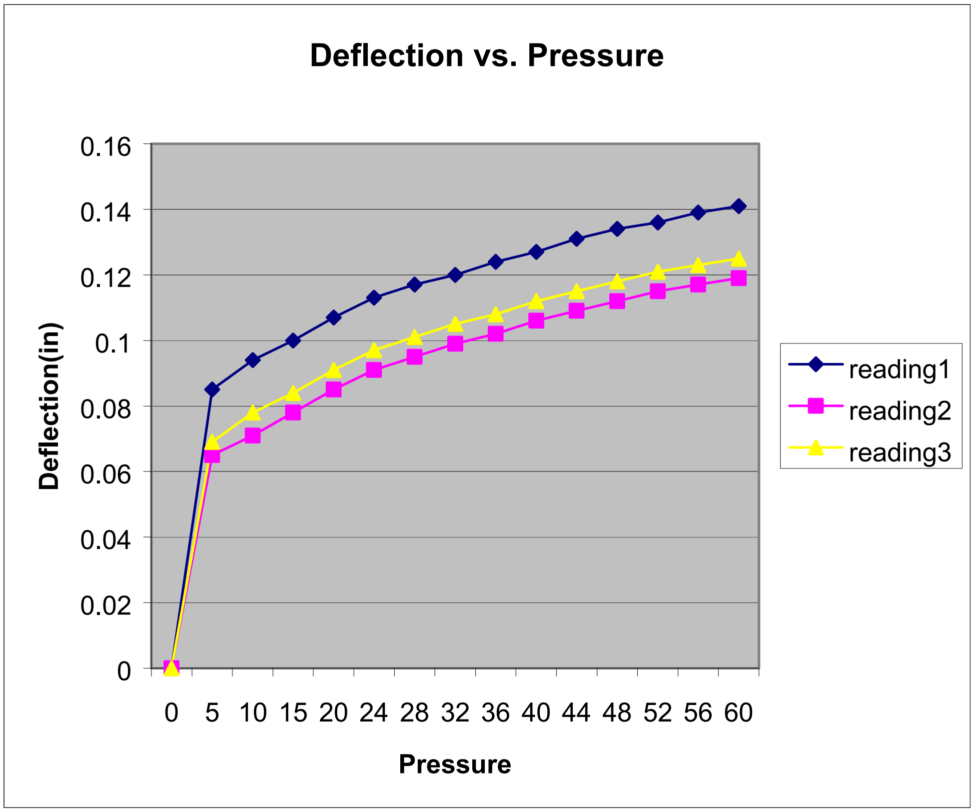


Figure 7. Deflection results for 0.033" disc.

Results and Observations

The graphs above illustrate an unexpected but important result. Each disc experienced some permanent deformation every time a set of readings was taken. Clearly, at some point the disc exceeds the elastic limit. Further evidence of this is given by the visible bulge that remains after the disc is unloaded, giving the initially flat disc a spherical shape (see Figure 8). Also note the general trend of reducing maximum deflection for each consecutive set of readings. Upon sudden reduction in pressure the disc does not regain its original shape instantly. Rather, it tends to regain its new initial state very slowly and gradually. To test the maximum pressure the disc could withstand before cracking, pressure up to 100 psi was applied to both the discs. However, spite of this high pressure, neither disc failed.

Sources of Error

Though the procedure was followed carefully to get the results as accurate as possible there are some sources of experimental errors. The following sources were identified:

1. Use of a tactile measurement instrument (dial gauge-least count is 0.001") to measure the deflection of the disc. This source of error, though very insignificant, reduces the accuracy of the deflection of the disc. Another source of error due to this instrument is the friction between the tip of the probe and the disc. To account for these phenomena,

all readings were assumed to have a general tolerance of about ± 0.005”. Three sets of readings were taken for each data point to account for this error.

2. Use of the polyethylene seal. For complete accuracy, the overall disc should be treated as a composite disc (polyethylene + Duraform). However, this is difficult to account for analytically. Thus, measures were taken to eliminate effect of the sheet on the deflection of the disc, such as making the sheet larger in the deflection zone so it is loose and does not provide significant resistance to the applied pressure. It is safe to assume that the pressure recorded is indeed the pressure applied to the disc.

3. There may be a very small amount of error involved in the overall experimental set up. As seen from the figure the set up is very basic with no built-in support structure. Rigidity is provided using clamps, which may not prevent slipping, though care has been taken to ensure no slippage.

4. The test discs are not exactly uniformly thick. This is a definite but unpredictable source of error.

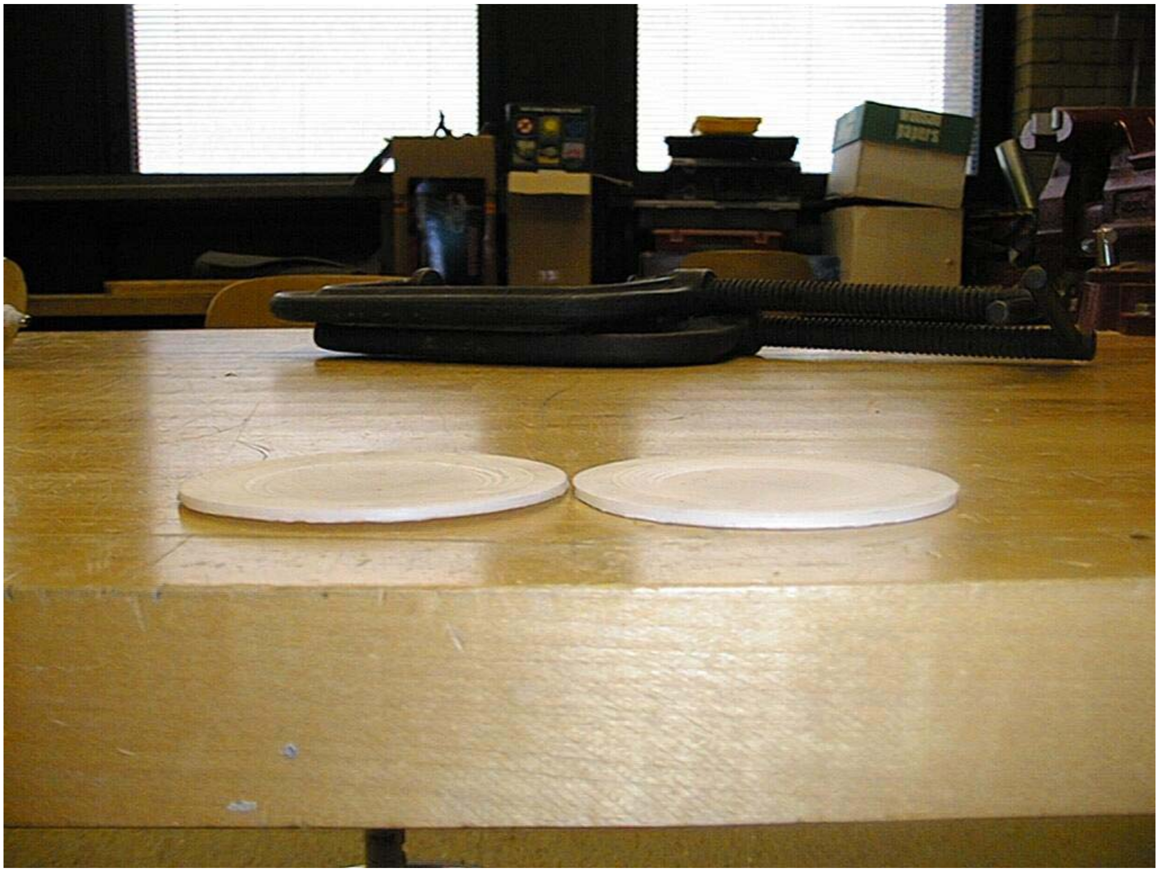


Figure 8. Undeformed disc before experimentation (right) and deformed disc after experimentation (left).

FINITE ELEMENT ANALYSIS OF DURAFORM DISCS

The goal of this research is to develop a finite element (FEA) based compliance model that can be used to design prosthetics sockets. This section describes the model developed and compares the results of the model to the experimental results presented in the previous section. All FEA results were obtained using ANSYS 5.5 from ANSYS, Inc., Canonsburg, PA.

The FEA analysis of each disc assumes that the disc is rigidly clamped at it periphery, thus simulating the experiment performed above. In order to be able to do the FEA, properties of Duraform such as the elastic moduli (E_x, E_y) and Poisson's ratio were needed. Due to layered nature of SLS, the resulting parts and elastic moduli are orthotropic in nature. We used the experimental results from [Watson, 1999] for these properties. In particular, a stress-strain curve was used rather than a single value for the elastic modulus. The curve used is shown in Figure 9, as plotted by ANSYS. The value for Poisson's ration was determined by solving a deflection relationship iteratively to correlate with the experimental results from the previous section. The computed value of Poisson's ratio was 0.406, which agrees well with values published by DTM Corp.

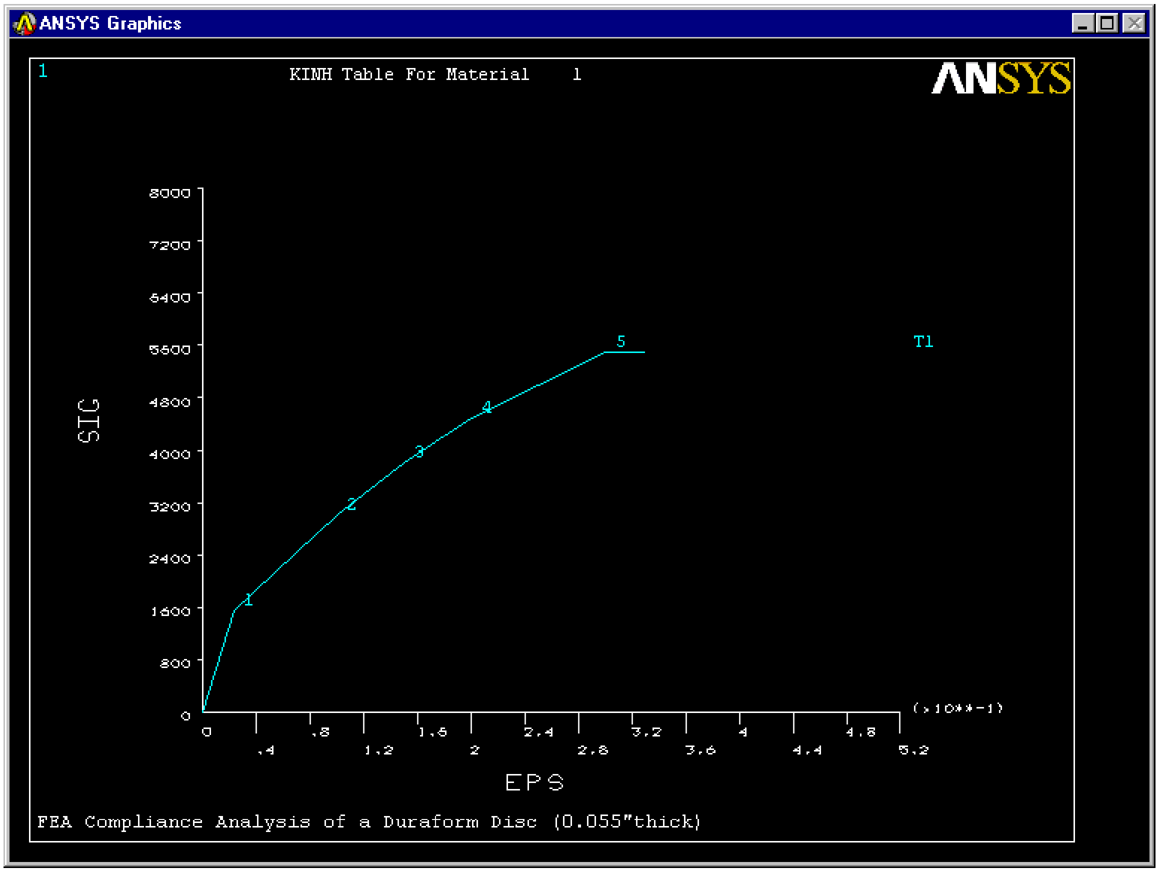
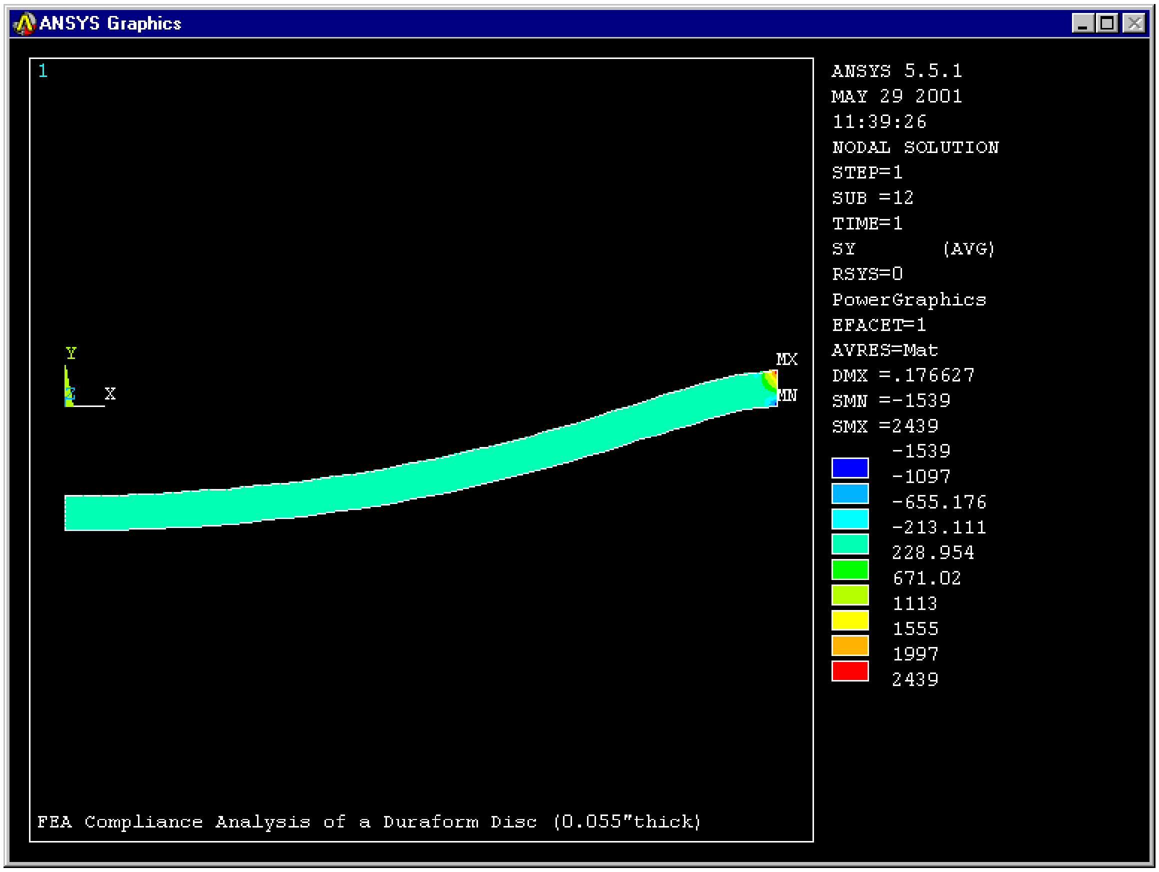


Figure 9. Stress-strain curve used for FEA.

Finite Element Model

The element PLANE42 was used for the analysis. This element assumes the behavior of the disc is axisymmetric and isotropic. Deflections and stresses were analyzed for the disc cross-section. Since the specimens can be considered thin discs, we assumed that E_y has no significant effect on the results. This assumption is confirmed by the stress distribution in the *y* axis direction, as shown in Figure 10, which shows very low and uniform stresses.



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FEA Compliance Analysis of a Duraform Disc (0.055"thick)
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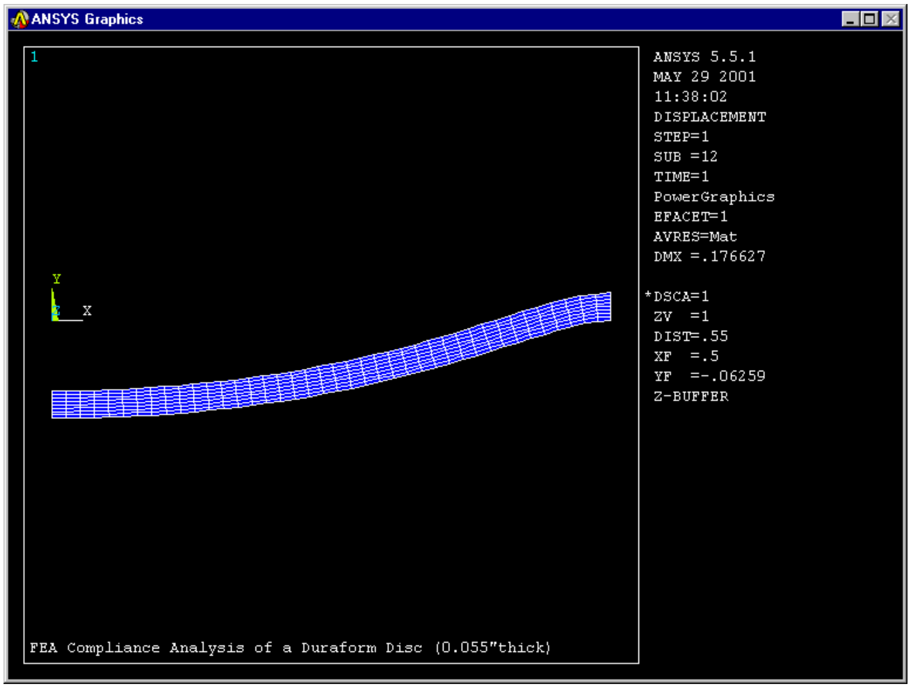
Figure 10. Stress distribution in the *y* direction.

FEA Results

Using these values for the mechanical properties, the finite element analysis yielded the results shown in Table 1. Figures 11 and 12 show the cross section of the deformed shaped and the stress distribution in the *x* direction, respectively, for the 0.033" disc. Pressure-deflection graphs for the experimental and analytical results for the 0.033" disc are shown in Figure 13. The figure shows there is good agreement between the two.

Table 1. Deflection vs. pressure results from FEA.

Pressure (psi)	Deflection at the center (in)
0	0
5	0.059988
10	0.083738
15	0.10023
20	0.11351
25	0.12478
30	0.13482
35	0.14409
40	0.15286
45	0.16120
50	0.16923
55	0.17704
60	0.18466



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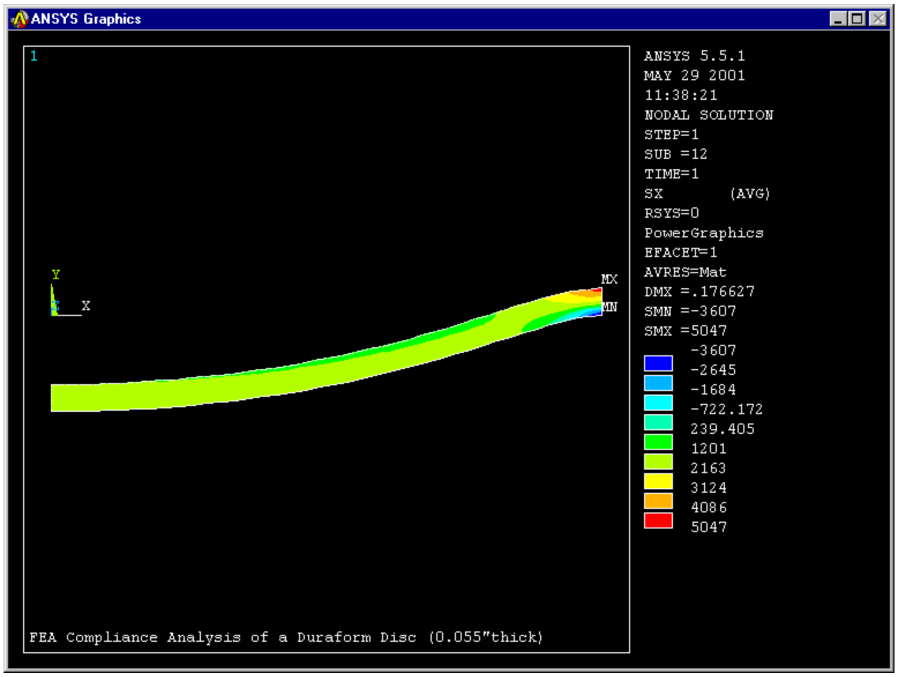
FEA Compliance Analysis of a Duraform Disc (0.055"thick)

Figure 11. Cross sectional deflection of disc in *x* direction.



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FEA Compliance Analysis of a Duraform Disc (0.055"thick)

Figure 12. Stress distribution of disc in *x* direction.

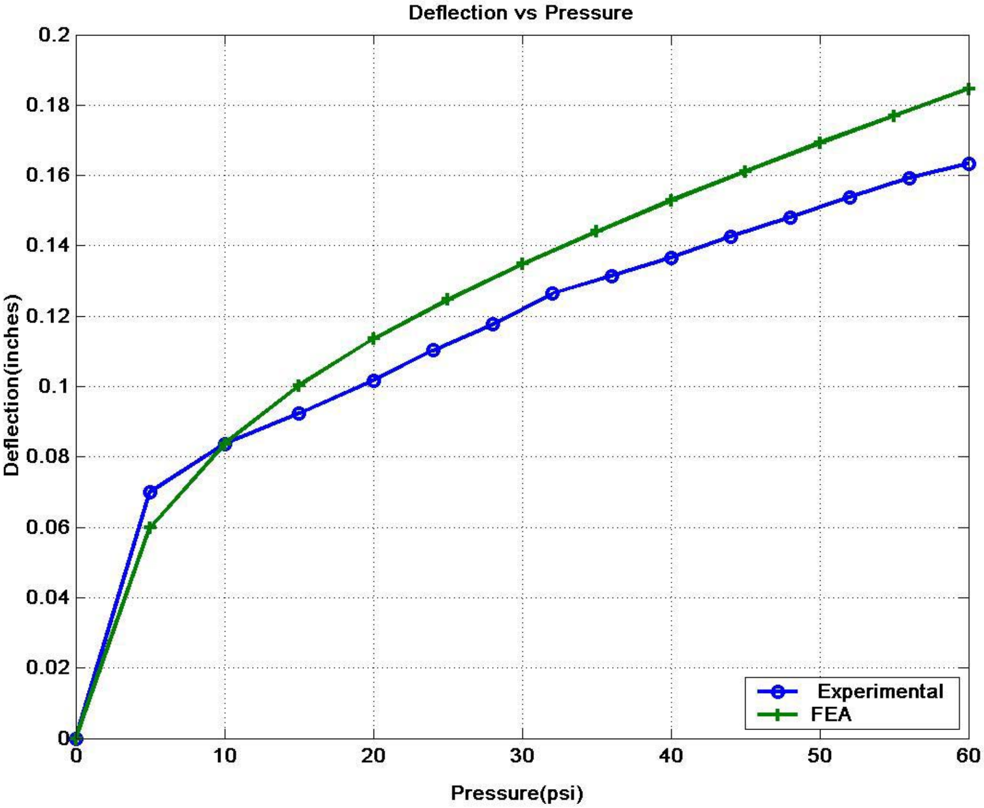

Figure 13. Pressure-deflection relationships from experimental and FEA results.

Analysis of Results

In order to quantify the match between the experimental and FEA results, a Kolmogorov-Smirnov Two Sample Test [Johnson and Leone, 1964] was performed on the two data sets. The two-sample Kolmogorov-Smirnov test determines whether two independent samples come from the same distribution by comparing the two-sample cumulative distribution functions. The test assumes that both samples come from exactly the same distribution.

Using SYSTAT, a statistics package from SSPS Science, Chicago, IL, the Kolmogorov-Smirnov two sample test was preformed with a significance level of 0.05. The results are shown in Table 2. The results show that the two distributions are from the same distribution with a confidence of 96.2 %. Thus, the important step of obtaining similar results from the experiments and FEA was achieved.

Table 2. Kolmogorov-Smirnov two sample test results.

Maximum Difference for Pairs of Variables		
	FEA	Experimental
FEA	0.000	
Experimental	0.2	0.000
Two-Sided Probabilities		
FEA	-	-
Experimental	0.962	-

CONCLUSIONS

The focus of the work reported here is compliance in single walled prosthetic sockets. To quantify the compliance of Duraform®, thin circular discs with varying thicknesses were subjected to pressures corresponding to those that would be experienced during gait by the amputee. The deflections of the discs were recorded as indicators of the degree of compliance. These results were compared to a finite element model of the discs. In order to obtain good agreement between the experimental and analytical models, a non-linear stress-strain curve for Duraform® was used.

The work reported here is part of an ongoing effort to improve the performance of prosthetic sockets using SLS. We have fitted several sockets to patients and performed limited clinical trials, with promising results. The next step is to use the results from the compliance tests to optimize the socket design. We also need to determine the durability of Duraform® sockets made with SLS. Also, more extensive, long-term clinical trials are necessary to prove the durability of these sockets.

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3. Stephens, S., *Design of a Compliant Prosthetic Socket Fabricated Using Selected Laser Sintering*, Master's thesis, The University of Texas at Austin, August 1999.

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