Bending Strength Test and Evaluation of a Transtibial Prosthetic Socket Fabricated by Selective Laser Sintering

by

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Supervisor, Richard Crawford: ____________________

Richard Neptune: ____________________

To the men and women of the U. S. armed services who

have lost life and limb in service to their country and who

know best that freedom isn't free.

Acknowledgements

I would like to thank Dr. Richard Crawford, my advisor, for his patience and guidance throughout the process, and Dr. Richard Neptune for his invaluable knowledge and insight. Additionally, this work would not have been possible without the patient efforts of Danny Burhan, Vinayak Dixit and especially Mario Faustini, all of whom assisted in setting up the bending test or producing the finite element analysis, or both. I would also like to thank Bill Rogers, Gordon Bosker and all the staff at The University of Texas Health Science Center at San Antonio, who provided valuable information. Finally, I would like to thank my family and friends who have consistently supported me in this and all my endeavors.

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Transtibial prosthetic sockets made using selective laser sintering (SLS) of Duraform™ PA have no documented failure data. In order to produce prostheses with safe weight and usage limits, a non-standard bending test was needed to determine the maximum safe loading of the socket and to recommend design improvements. The bending test was designed to replicate forces experienced by a wearer stepping down and forward as from a slight elevation. This test, along with a finite element analysis, provided information about the force limitations and weakest point of the socket. Suggestions for improving the design incorporated this information and laid the groundwork for further improvements.

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Chapter One: Problem Introduction

Introduction

Cooperative research on the benefits of custom manufactured sockets for transtibial prostheses is making impressive strides towards a dramatically improved product. The benefits include the advantage of compliant sockets, formed using a combination of layered fabrication and computer aided design. The current method of socket fabrication is laborious and time consuming. A more current method, which incorporates selective laser sintering (SLS), will produce better sockets more quickly and with a greatly reduced requirement for human labor. Additionally, the SLS process can incorporate local geometric changes to provide a better fit with a higher comfort level.

1.1 Transtibial Prostheses

Transtibial prosthetic sockets made using SLS have no documented failure data. In order to determine safe weight and usage limits, a non-standard bending test must be designed and employed in order to determine the maximum safe loading of the socket and to focus on areas for design improvements.

A typical example of an SLS socket is shown in Figure 1.1. As this example shows, one feature of the SLS socket is the attachment fitting which is formed as part of the solid socket. The socket and prosthetic foot are joined by a pylon, which is often made of an aluminum or titanium alloy. Many types of prosthetic feet are available with varying levels of complexity and cost.

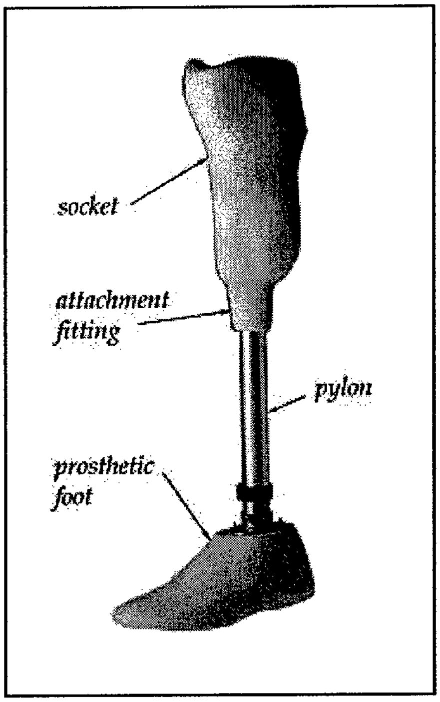

Figure 1.1

Basic prosthesis assembly using SLS socket. [14]

1.2 Selective Laser Sintering

SLS produces custom-designed objects by creating layers from powder nylon materials. The fine powder (~ 50μm particle size) is spread to a uniform thickness by a roller. A CO_2 laser then traces the cross section of the object. The laser heats the powder to a temperature at which the particles actually flow together, creating a solid object one layer at a time. After a layer has been created, the platform holding the object is lowered and another layer of powder is rolled over the surface. [9] The configuration of a typical SLS machine is shown in Figure 1.2.

There are a number of advantages to using SLS for manufacturing prosthetic sockets. Because it employs Computer Aided Design (CAD) and laser precision, it achieves a higher level of accuracy than can be expected from a man-made product. Changes to the design may be accommodated without significant additional human labor. Objects requiring internal voids present no additional challenge for SLS production as they do with other manufacturing techniques. Finally, several objects may be produced simultaneously. The only limitation is the size of a particular SLS machine's workspace (e.g., 61 cm in diameter and 46 cm high for a LaserForm™ oven or W370 x D320 x H445 mm for a Vanguard System ™ [1]).

A particular socket design was developed by a team from the Mechanical Engineering Department at The University of Texas at Austin in conjunction with the Department of Rehabilitation Medicine at The University of Texas Health Science Center at San Antonio. The socket design took full advantage of the benefits and versatility of SLS technology.

A prototype of this socket was designed and manufactured using SLS technology; however it failed during normal use. Specifically, the failure occurred as a result of the wearer stepping from a bus to the curb. In order to avoid this type of failure, a bending test that replicates the forces involved in that scenario is needed.

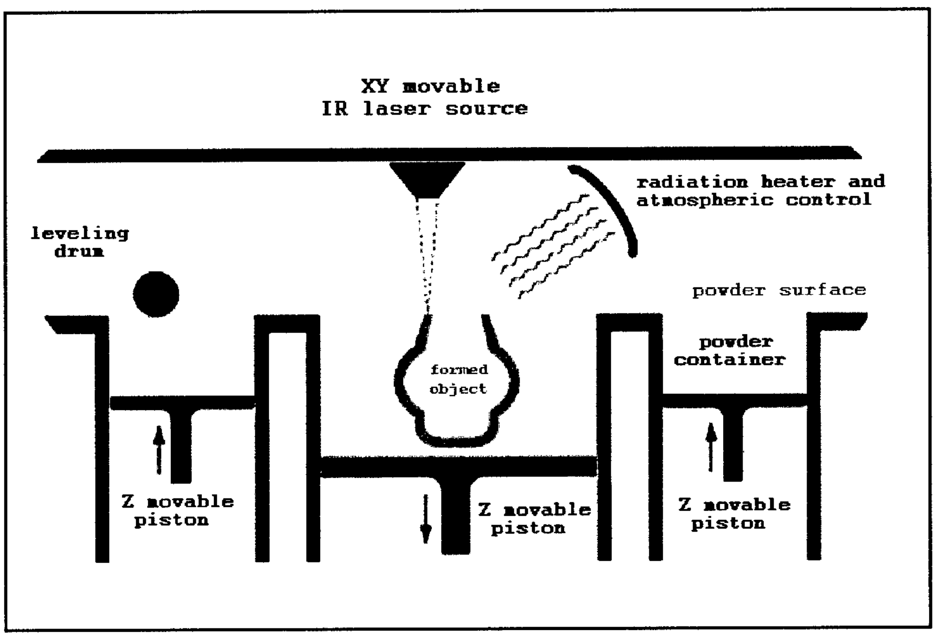

Figure 1.2

Diagram of a typical SLS machine. [9]

1.3 Objectives

The objectives of this research are:

1. Develop a laboratory test to simulate real-world forces experienced by a user while stepping down and forward.

This test is intended to replicate those forces that would most likely cause the socket to fail due to normal use. Excluding athletic endeavors, the scenario investigated was considered the most extreme force that a user would place on the socket during normal use.

2. Develop a finite element model (FEM) and finite element analysis (FEA) to predict the expected initial point of failure and the maximum stress associated with the failure load.

The FEA should be designed to replicate, as closely as possible, the conditions of the experimental test in order to provide a basis for comparison. The FEA provides an analytical approach to determining the weakest point of the socket. Ideally, it will indicate a weak point or area similar to that observed during the experimental test, thus providing confidence in the validity of the FEA approximation.

3. From the results of the lab test and FEA, establish a safe weight limit for the given socket size and recommend focus for improved design.

The qualitative and quantitative results should highlight a particular point or area which would most benefit from redesign. The results will also be evaluated to determine a safe load limit for the particular socket size tested.

4. Identify areas for future work.

Suggestions should be developed for improvements to the bending test, if any, and the FEA. Possible sources of error should be explored with suggestions for overcoming them. Also, a scope of work that would appropriately continue the progress made in this thesis should be identified.

Chapter Two: Background

2.1 Transtibial Prosthetic Socket

A transtibial prosthesis is appropriate for an individual who has a functioning knee joint but is missing some portion of the lower tibia and fibula. This kind of amputation, also referred to as "below-the-knee" (or "BK") results in a limb similar to the one depicted in Figure 2.2. In the best cases, a person using a transtibial prosthesis can perform as well as someone with both legs intact, even competing as a professional athlete in some instances.

Consumer demand for state-of-the-art prostheses may motivate private industry to supply better products. However, the motivation to improve the quality of this type of prosthesis is not limited to commercial entities. As an example, the U. S. military is extremely interested in returning service members wounded in combat to fully-functioning status. As of March 2004, Walter Reed Army Medical Center had already treated roughly 70 amputees wounded in the current war in Iraq [8]. Amputations of the leg are all too common in this conflict as a result of land mines and road side bombs. The Army's perspective on rehabilitating soldiers is not just to provide an adequate prosthesis, but one that enables injured men and women to perform at the same level they knew before they were wounded.

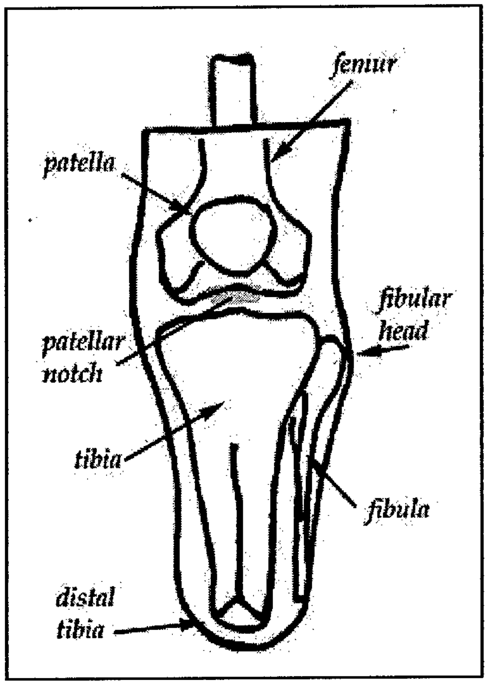

Figure 2.2

Front view of the left remaining limb of a below-the-knee amputee. [14]

The military is not alone in this goal. The Department of Rehabilitation Medicine at The University of Texas Health Science Center in San Antonio often provides prostheses for individuals who may not be able to afford the more expensive models offered by private industry. The Department states that "the goal of rehabilitation is to restore an ill or injured patient to self-sufficiency or to gainful employment at his or her highest attainable skill level in the shortest possible time." [15]

The widespread demand for a better prosthesis is being met through improved technology. One of the key elements of an effective transtibial prosthesis is the socket. The socket serves as an interface between the residual limb and prosthetic components. The performance of the entire apparatus is directly related to the level of comfort afforded by the socket. In order to achieve a high level of comfort and performance, the socket must fit the individual as precisely as possible.

2.2 Fitting the Socket

The process involved between the initial trauma of the amputation and the successful fitting of a socket is a complex and dynamic task. No two individuals will have the same dimensions or sensitivities. Currently, the development of an adequate socket prosthesis is a labor-intensive process that relies primarily on the artistic skill and experience of a prosthetist.

The amputee undergoes initial measurements of the remaining limb. A cast is made of the limb using a plaster mold or a high resolution scan of the amputation is fed to a carving machine which creates a foam template. A plastic socket is then formed using either the plaster or foam template. During this process, the prosthetists combine their personal experience and whatever information the amputee can provide to guide them in making adjustments to the shape of the cast. Such information might include identifying specific locations that cause the individual pain or discomfort [11].

Once the template is adjusted to fit the specific shape of the remaining limb, the actual socket is formed on the template. The socket is often made of a composite such as carbon fiber with a polymer matrix. It is often formed onto the template using vacuum molding [13]. Once the socket has been formed and reaches adequate rigidity, the prosthetist must perform some detailing, such as the smoothing of rough edges, before it is a finished product and ready for use. The large amount of manual work involved in the process allows room for human error. The quality of the finished product is affected by the skill of the technicians and the condition of the materials and equipment used.

Additionally, if the patient has recently undergone amputation and is being fitted for the first time, he/she will experience dramatic changes in the size and shape of his/her residual limb. As the swelling subsides and the muscles atrophy, the shape that must be accommodated by the prosthetic socket will change considerably. These changes commonly require up to a full year before a stable size and shape are reached.

Clearly, the production of a single socket is a complex procedure and can require an average of eight dedicated hours by a prosthetist to produce a single socket. Considering the variable nature of a newly amputated limb, a more efficient method of production is needed. Producing the socket using composite technology is not a simple or forgiving endeavor. Simple errors such as a poor mixing of the epoxy or an overdone manual adjustment to the template may cause an entire socket to be ruined. Additionally, the cost to produce a socket is affected by the amount of skilled labor required for its creation. As some lower leg prostheses can cost up to $100,000 [8], a more economic approach to socket production is highly desirable.

2.3 Recent Developments

Selective laser sintering (SLS) offers a superior method of producing customized sockets. SLS is useful in situations where a component is custom-made and not required in large quantities. Because SLS operates by converting a computer generated design into a series of layers to create an object, it requires very little human labor. A qualified operator only needs to input the desired design and allow the machine to create the socket. The only challenge is in adjusting the design for the individual, but compared to conventional methods, SLS provides a dramatically faster and less labor intensive process. Additionally, socket designs may easily be archived so that when a person needs a replacement (assuming no changes to the socket are needed) it is much easier to produce than starting over completely.

One popular material used in the SLS process is Duraform™ polyamide (PA), which is a type of nylon powder. Duraform™ boasts an impressive array of applications such as form, fit/snap-fit, and functional testing, durable patterns for sandcasting and silicone tooling and production parts. However, the nature of Duraform™ is such that its stress/strain properties are affected by the orientation in which the final product is manufactured and the condition of the powder used. This variation translates to a lack of expected failure tolerance for customized sockets and no safety guidelines can be provided about appropriate weight loads without considering the specific shape.

The socket developed by a research team from The University of Texas at Austin and The University of Texas Health Science Center at San

Antonio included significant improvements over conventionally produced sockets. One of these improvements is the use of compliant features which appear as depressions or cut out sections on the socket's surface in Figure 2.3. These features make use of Duraform^{TM}'s flexibility and reduce pressure on sensitive areas but they do present additional challenges.

Specifically, a prototype of the design was manufactured from Duraform^{TM} and fitted for a user in an experimental study. The wearer stepped off of a bus and down to a curb and shortly thereafter discovered a large crack at the bottom of the socket below the distal end compliant feature as noted in Figure 2.3.

Fortunately, the failure was not catastrophic at the moment the individual stepped onto the curb, as this may have caused an injury. However, the potential for injury was obvious and the incident certainly demonstrated inadequate load bearing properties for this type of use with the current socket design. In order to begin offering the SLS sockets on a large scale, prosthetists need reliable failure data and safe load limits for normal use. Additionally, analytically determined design improvements must be explored to take advantage of the full potential of SLS technology and Duraform^{TM}'s beneficial properties.

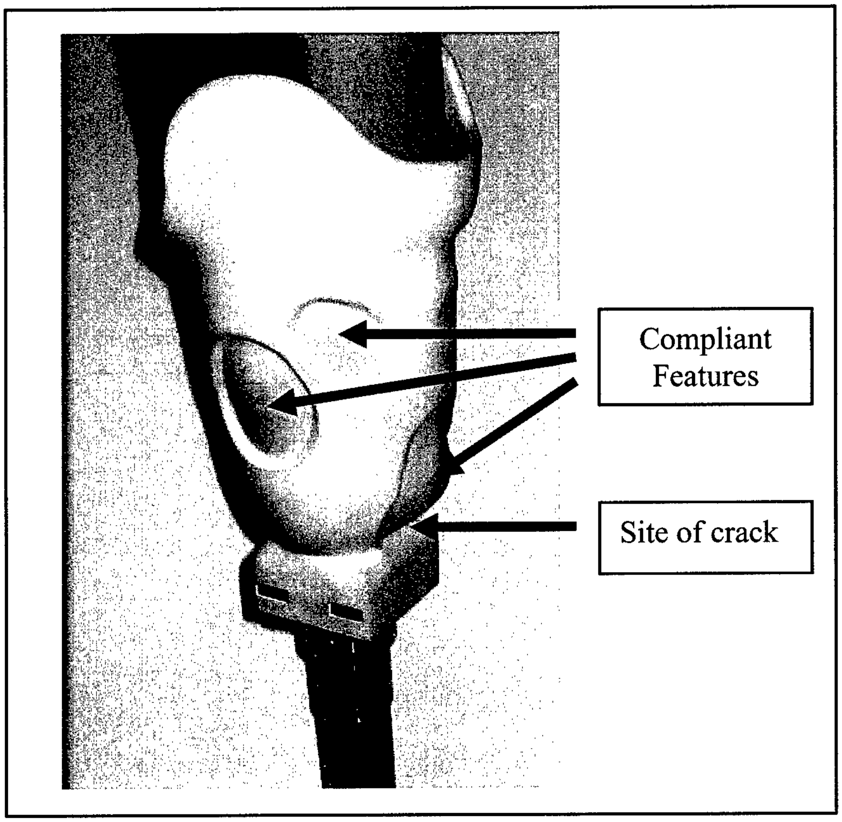

Figure 2.3

Socket to be tested with site of prototype's crack indicated.

Due to the fact that Duraform^{TM}'s properties are configuration dependent, the results of a FEA alone cannot be assumed to provide sufficient evidence for the socket's failure limits. The FEA results are dependent upon the accuracy of the data used in the simulation. The material properties [2] used for the simulation are those published by 3D Systems Company and might not be the actual properties possessed by the socket. It should be noted that the socket tested was created in a vertical orientation.

An experimental test must be developed in order to determine the socket external loading limits. The FEA results can then be compared to the test results. This may also provide some insight into how much variation exists between different models regarding the maximum stress that a particular Duraform™ socket may withstand.

Chapter Three: Bending Test

Introduction

A bending test was developed to simulate the real world situation of a user stepping down and forward. The test setup recreated the forces produced during the heel strike in this scenario. The results of the bending test provide the maximum forward or horizontal component of the heel strike force that causes the socket to fail. A force analysis was performed to determine the best method of modeling the forces. This analysis guided the set up of the bending test.

3.1 Force Analysis

In order to relate the bending test to the actual forces experienced by the socket during normal use, it was necessary to perform a force analysis for comparison. Gait data indicating force vectors were measured in the gait lab located at The University of Texas Health Science Center at San Antonio [15]. The bending test was designed to consider a subset of all the external forces acting on the socket.

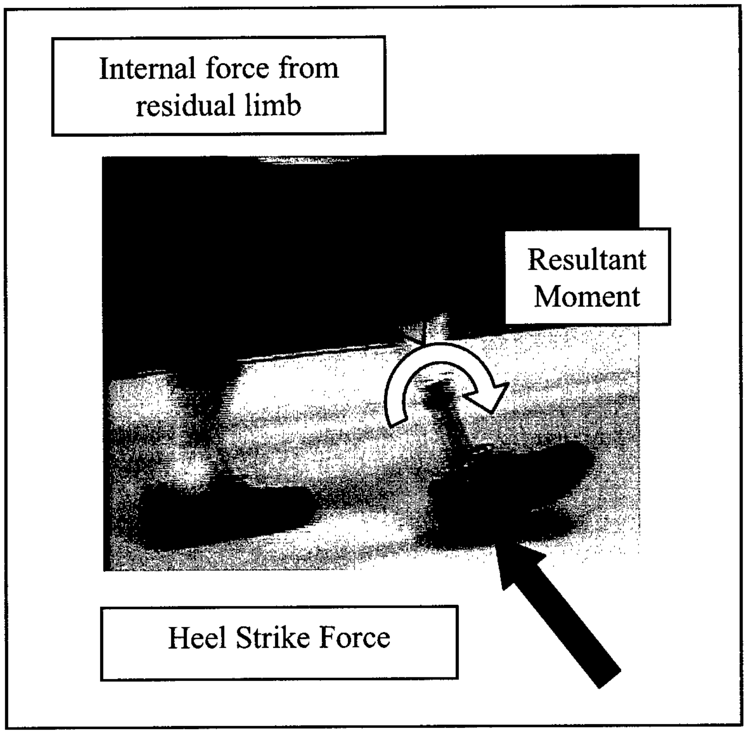

Figure 3.1

Forces indicated on an individual using a transtibial prosthesis.

(Note: force vectors are not drawn to scale.)

The forces experienced in a real world scenario can be visualized as shown in Figure 3.1. For the purposes of the test, several assumptions must be made about the scenario to be modeled. Arguably, these assumptions would not hold true for every individual performing this action, every time they performed it. However, it is a possible scenario and one which produces the largest bending moment on the socket. In designing a failure test, the worst case scenario should be used as a basis for force analysis. That worst case for this study is the one that applies the largest percentage of the user's body weight to the bending moment.

The following assumptions were made with the objective of creating that worst case scenario. First, it was assumed that the person is traveling in a forward motion, along a single plane (designated as the X-Y plane for comparison) and that lateral movements in the Z-direction are small enough to be considered negligible. This makes it possible to use a planar model.

Second, the greatest portion of the resultant moment is created about the lower end of the socket, near the base. This assumption is based upon the relative flexibility and motion of the user's remaining limb, the Duraform™ socket and the metal pylon and attachments. The force applied by the remaining limb, acts upon the interior of the socket along a surface that curves between the anterior and distal planes.

Finally, the socket is assumed to be in a momentary state of zero rotational and translation acceleration. For the purposes of this experiment, only the maximum loading experienced by the socket is of interest. Therefore, it is necessary to consider the body at a moment where the forces are greatest. This would occur when the heel strike force and the force applied by the individual are acting upon the prosthesis but it has not yet begun to move as a result of those forces. The forces acting upon it will cause it to rotate (in the X-Y plane), but in the instant before that motion begins, the forces are creating the greatest bending moment that the socket will experience. It is reasonable to assume that this takes place very soon after the moment of heel strike.

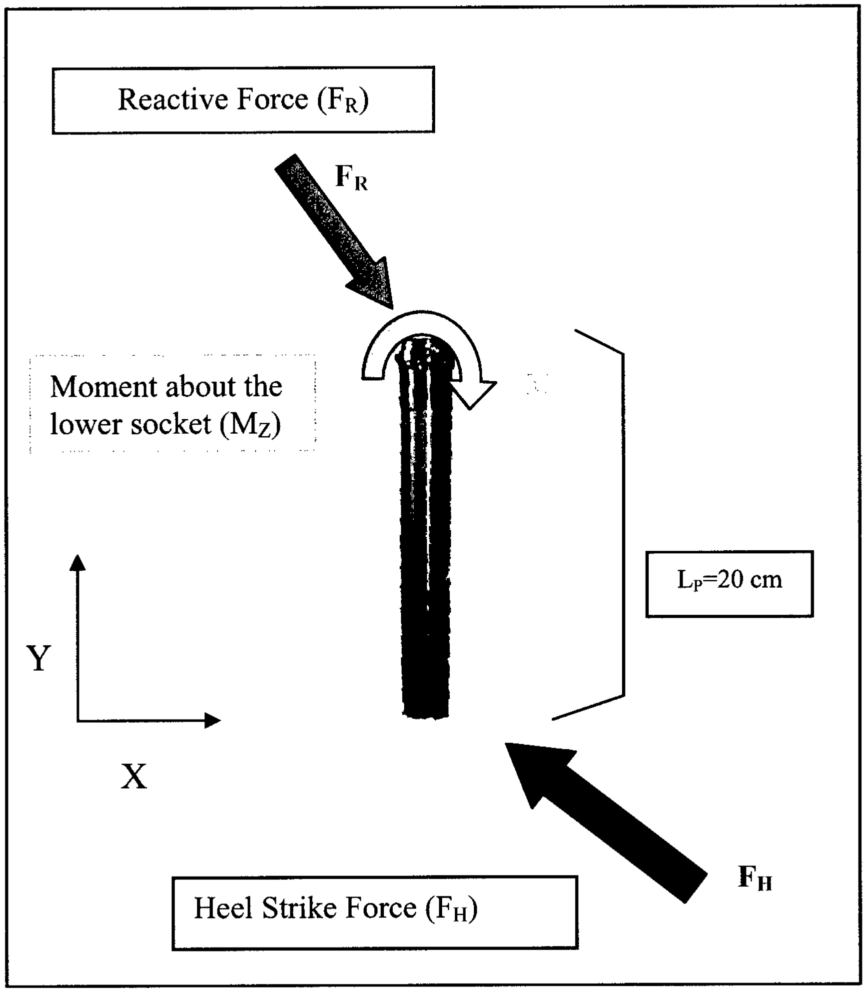

Figure 3.2

Free body diagram of pylon and attachment fitting with actual forces experienced at heel strike.

In order to fully understand the manner in which the forces interact, it is helpful to first consider the forces acting upon the pylon and attachment fitting only. Figure 3.2 shows the free body diagram. Breaking the vectors into X and Y components results in the following equations with the components illustrated in Figure 3.3.

$$F_P = F_{Px} + F_{Py} \text{ and } F_H = F_{Hx} + F_{Hy}$$

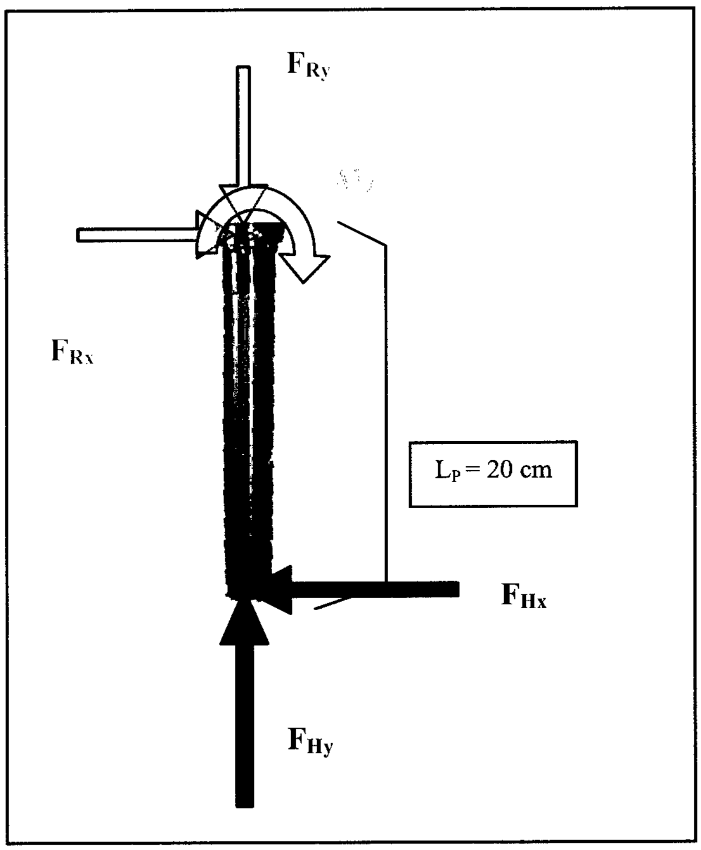

Figure 3.3

Socket with component forces displayed.

Summing the moments about the attachment fitting,

$$(F_{Hx} * L_P) - M_Z = 0$$

Therefore,

$$(F_{Hx} * L_P) = M_Z.$$

The effect of compressive forces on the socket integrity is studied in a separate work [5]. While the vertical force components certainly play a role in the experimental scenario, it is the bending moment that is of most interest. It is this moment that is at least partially responsible for the type of socket failure which this work seeks to replicate. It should be noted that shear forces on the socket may also contribute to the failure, but those forces were not studied here.

Now that the bending moment and forces at the attachment fitting are known, the socket must also be considered. As the person steps down and the heel strike induces the moment about the attachment fitting, the residual limb will act to prevent the socket from rotating forward due to the moment. This is best modeled by constraining the socket in all directions as illustrated in Figure 3.4.

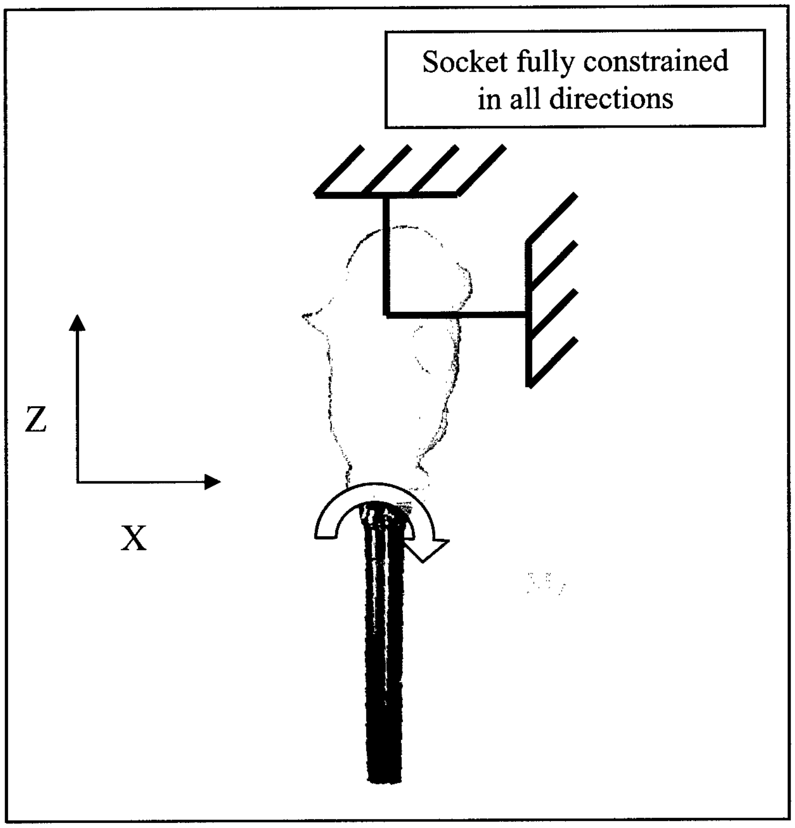

Figure 3.4

Free body diagram of socket with bending moment.

In order to recreate the bending moment, the socket is constrained in every direction and the horizontal force applied at the foot. This is an especially desirable model as it allows for the limitations of test equipment. Specifically, the equipment used for the bending test is a MTS 810 manufactured by MTS Systems Corporation, Eden Prairie, MN. This model can only apply compressive or tensile force in a vertical direction. By minimizing the required inputs to the model to one active force, the test setup is simplified. (See Figure 3.5.)

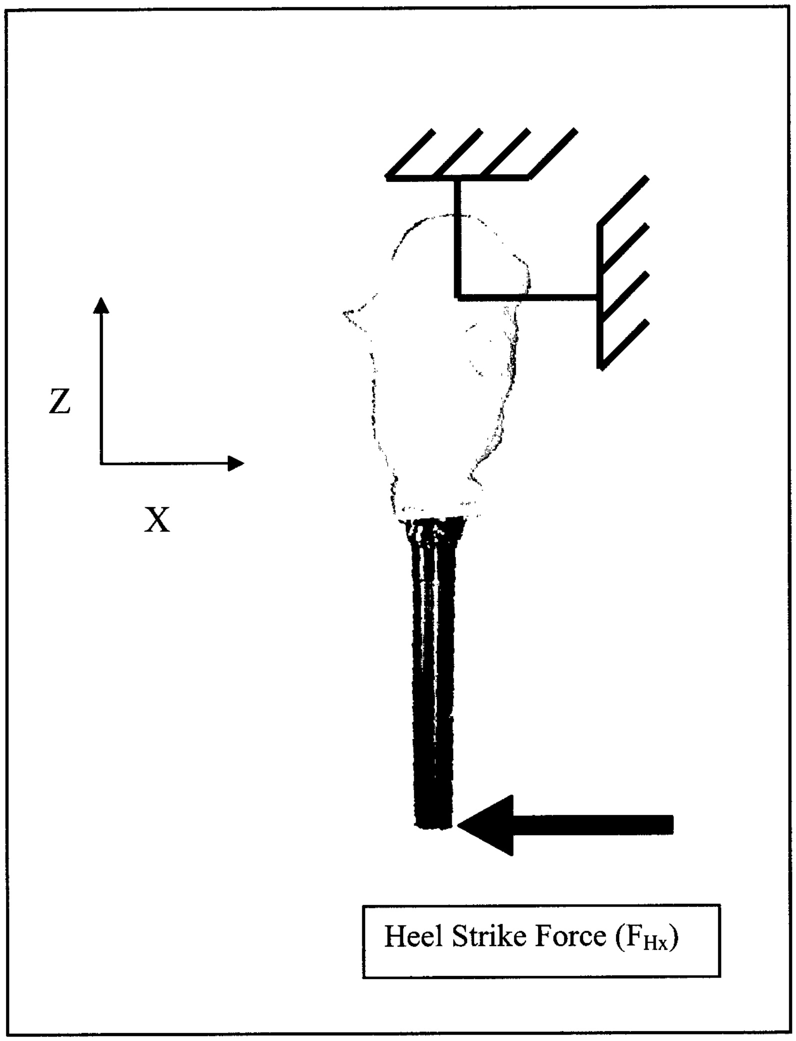

Figure 3.5

Free body diagram of socket with equivalent forces.

3.2 Test Setup

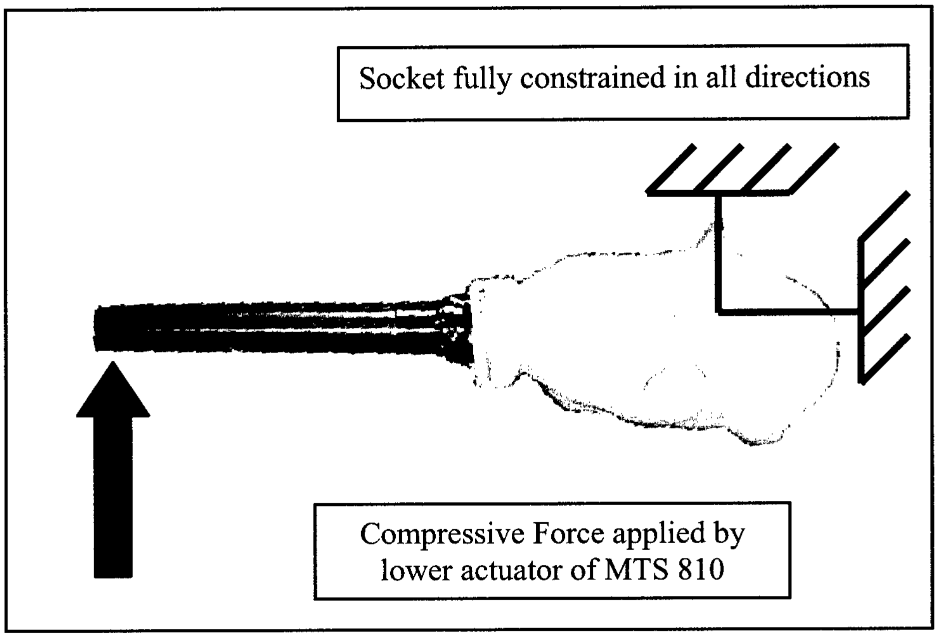

Figure 3.6

Model rotated to accommodate MTS 810 geometry.

In order to accommodate the geometry of the MTS 810, the assembly was rotated 90 degrees to achieve the set up shown in Figure 3.6. The effect of gravity on the assembly is not of particular concern as it does not significantly affect the moment. Therefore, this orientation of the socket does not affect the results. However, in actual testing, an unforeseen obstacle resulted from the lack of compressive vertical components.

The lower actuator of the MTS machine was equipped with a castor designed for a cylinder of 1 inch diameter (standard aluminum pylon used with prosthesis is a hollow cylinder with 3 cm outer diameter). The socket was initially constrained using a molded urethane form inside a commonly-used rubber foam padding sock. However, the natural compression due to gravity that holds the remaining limb inside the socket during normal gait was absent in this configuration. The sock's low friction characteristics allowed it to slip with a minimally applied force to the pylon. (See Figure 3.7.)

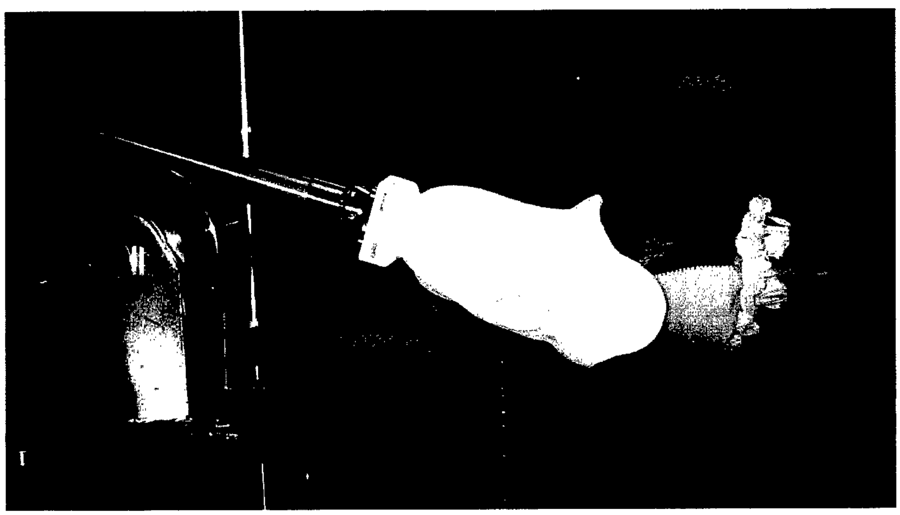

Figure 3.7

Photograph of socket slipping off of padded sock during test.

In order to overcome this obstacle, the urethane form and padded sock were replaced with a fill of Rockite™ plaster with casting sand at the base of the socket to minimize alterations to the Duraform™ characteristics. While this was not ideal because the plaster changed the Duraform™ response where the two came in contact, it was the best solution for the equipment limitations. The casting sand allowed the lower portion (approximately 4 cm) to react to the force naturally (ramifications of using the plaster are discussed in a later chapter). The final test setup is shown in Figures 3.8 and 3.9.

The following equipment was used for the socket bending test:

1. MTS Model 810 machine (in compression mode) with all recording components
2. Work table with added weights for stability
3. Vice clamp (with wood pieces for height adjustment)
4. Steel castor (designed to fit 1 inch pipe) with custom attachment for MTS machine
5. Socket assembly
   - Duraform™ PA socket
   - socket base attached to aluminum pylon (3 cm diameter) using standard attachments (no artificial foot)
   - steel pipe placed inside the socket and held in place with Rockite™ plaster
   - casting sand in the bottom-most portion of the socket (about 4 cm deep) to prevent plaster interfering with Duraform™ behavior

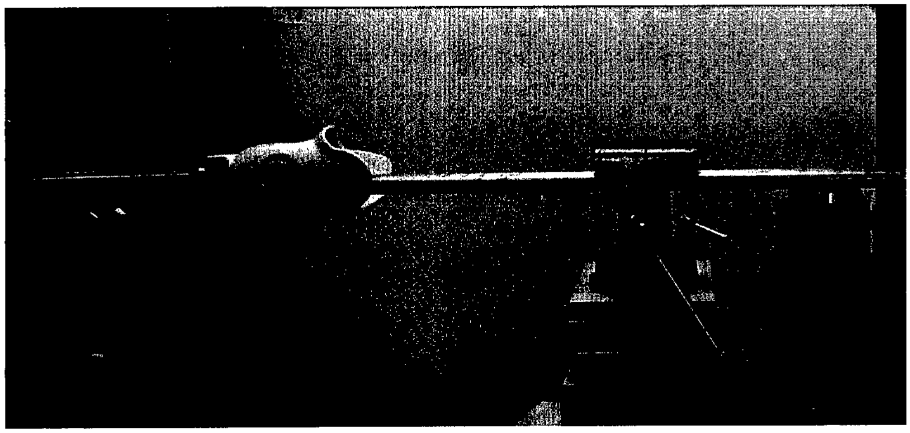

Figure 3.8

Side view of final test setup.

Figure 3.9

Front view of final test setup.

3.3 Test Protocol

The following protocol was followed for the socket bending test:

1. Determine required height of socket assembly:

The MTS machine has a limited range of motion. This requires that the socket assembly be positioned in such a way that it allows the greatest displacement of the free end of the pylon (hereafter referred to as the free end). The required height is determined by placing the free end on the castor when the bottom actuator is in the lowest initial position from which it can record measurements.

2. Position vice on table at appropriate height.

For the table used in this instance, several pieces of wood were used as spacers to provide extra height. The vice was secured to the table by means of specially ordered long screws.

3. Create socket assembly as described earlier.

4. Secure socket assembly in vice with free end resting on castor.

The end of the steel pipe which extends from the interior of the socket should be given additional stability by placing a stack of weights or other relatively incompressible object. This prevents the pipe from slipping inside the vice.

5. Zero out the MTS machine.

A qualified operator should perform tasks directly associated with the movement and data recording of the MTS 810.

6. Apply vertical force and record force and displacement.

Carefully observe the socket as the force is increased in order to determine the location of the initial crack. Safety precautions for personnel include wearing safety goggles and maintaining a safe distance from the socket.

7. The test is complete when a crack becomes visible and the socket no longer bears the applied load.

Duraform™ PA is sufficiently brittle to cause the entire base of the socket to snap off within a few seconds of a crack becoming visible to the naked eye. However, in the event that this does not occur, the test is complete when it is clear that the socket is no longer capable of sustaining a load due to structural failure. The MTS 810 load indicator should display a dramatic decrease in applied force despite continuing increases in displacement.

3.4 Test Results

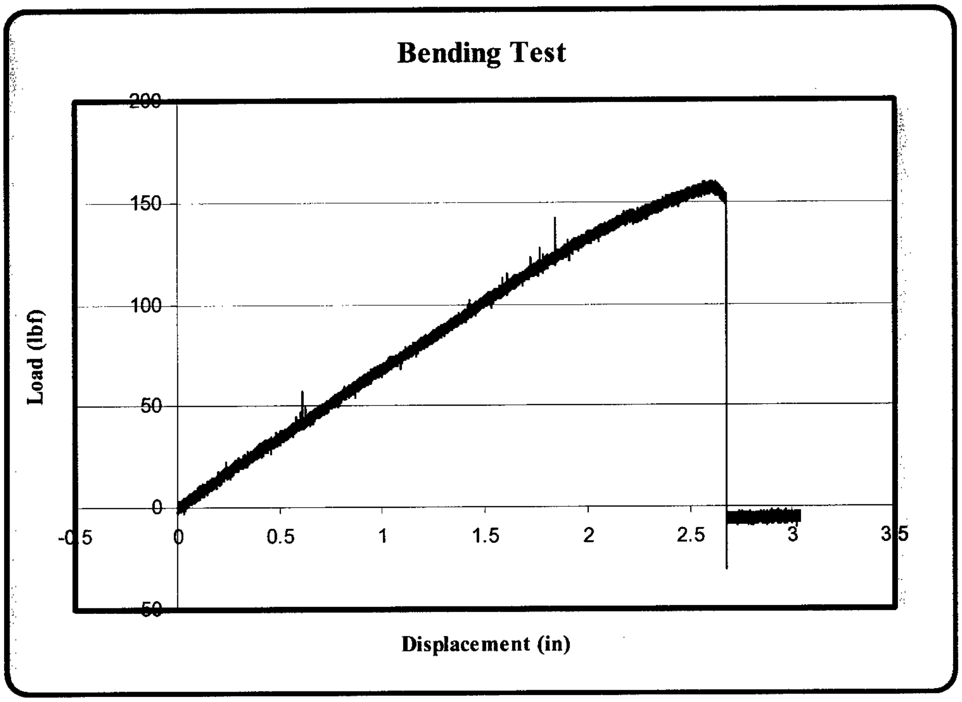

Figure 3.10

Graph indicating applied load and displacement of free end of socket assembly.

As shown in Figure 3.10, the maximum load reached before the socket failed was 159.929 lbf. The displacement at this load was 2.567 in and the maximum displacement was 2.677 in before failure occurred. The socket tested is sized for an individual of approximately 140 lb.

By visual inspection, the crack began at the bottom center of the distal end compliant feature, just at the point where the feature touches the socket base. (See Figures 3.11 and 3.12.) It spread quickly from there and the entire base snapped off within a few seconds of the appearance of the initial crack. The break was clean and no pieces of recognizable size shattered or splintered from the socket or the base.

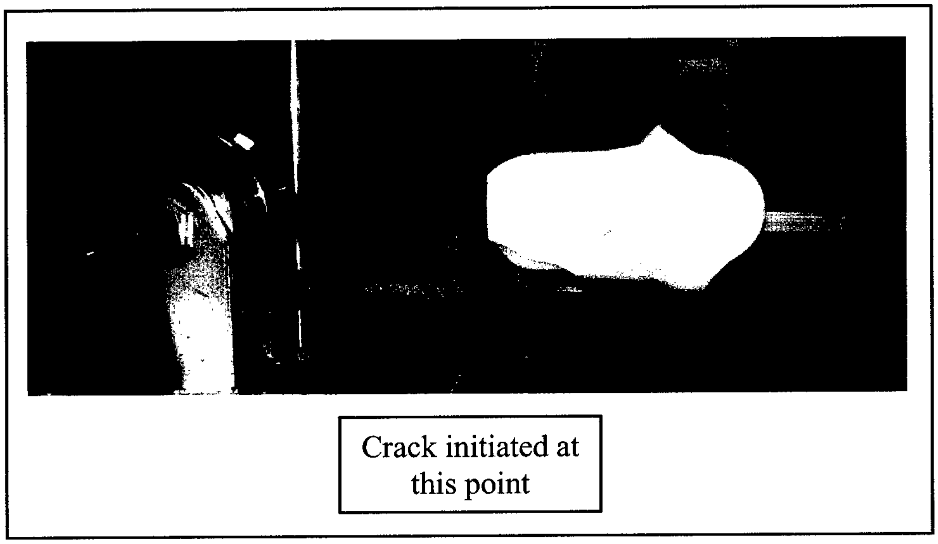

Figure 3.11

Photograph of failed socket with point of crack initiation indicated.

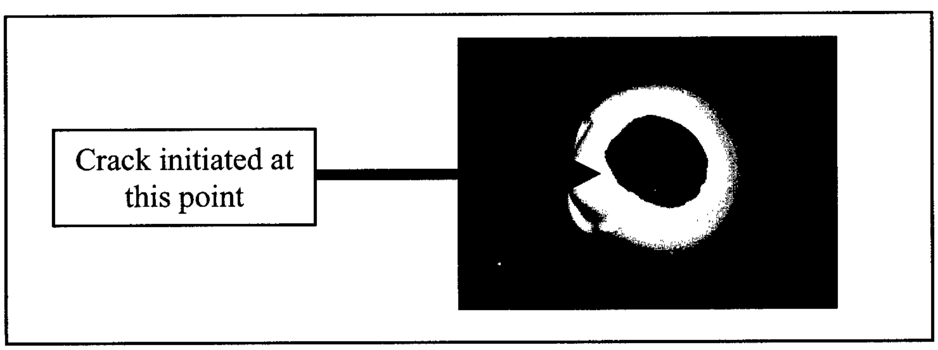

Figure 3.12

Broken socket viewed from the distal end with casting sand visible.

Summary

The force analysis discussed in this chapter provided the best method of modeling the forces involved when a user is stepping down and forward, specifically at the moment of heel strike. These forces were reproduced as closely as possible in the set up of the bending test with particular assumptions noted. The results of the bending test indicated a maximum horizontal (X-direction) component of the heel strike force that caused the socket to fail. The results of the test will be used for comparison with a finite element analysis.

Chapter Four: Finite Element Analysis

Introduction

A finite element analysis (FEA) complements the results of the bending test by providing an analytical approach to the same question of failure load. While most FEA software is not explicitly recommended for determining the failure load for a particular object or material, it provides data that may be compared to the results of the bending test. This comparison may validate the FEA results or provide insight about ways to improve the FEM so that the FEA maximum stress values are in better agreement with the experimental results. The FEA will use material data and loading that imitate the conditions of the bending test as closely as possible.

4.1 Description of Model

Finite element analysis serves as a useful aid for numerically solving differential equations relating to stress analysis. In this investigation, IDEAS version 10 (EDS, Plano, TX) finite element analysis software was employed to provide a simulation of the stress experienced by the socket. The software provided a means of comparing the experimental results with expected results based on the published Duraform™ material properties. It is not feasible to test every socket experimentally. A comparison of the

FEA and experiment results for the socket tested in this research will help in interpreting FEA results for other sockets without failure testing.

In order to simplify the simulation, the entire socket was not included in the finite element model. Instead, a truncated model, shown in Figure 4.1, was used without the complex geometry of the upper half of the socket. The material strength of Rockite™ plaster, which filled the majority of the socket's volume, is much greater than that of Duraform™. Failure due to compressive loads for fully set Rockite™ plaster occurs with a stress of more than 200MPa under loads of more than 16,000 lb [12] as compared to the 44MPa provided as Duraform™'s maximum stress.

Given the dramatic difference in material properties and the fact that the experimental load never exceeded 160 lb, it is safe to assume that no significant displacement occurred between the upper and lower portions of the socket that were fused to the plaster. This eliminates the need to include the top half of the socket as the stress of interest occurred due to displacement between the model's lower extremity and the area where the plaster adhered to the socket. Based on the relative material strengths of the Rockite™ plaster and sintered Duraform™ powder, it is reasonable to assume that throughout this area the plaster properties determined the response of the socket more than those of the Duraform™ material.

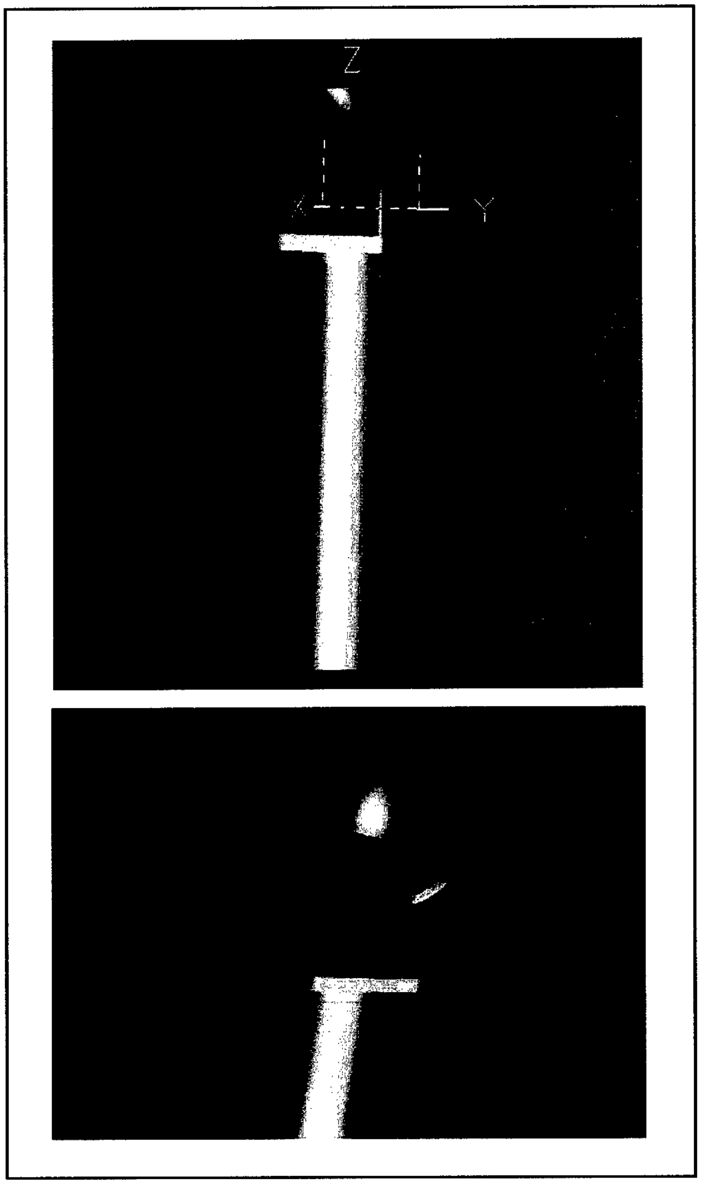

Figure 4.1

Various views of the truncated model of the socket and pylon.

Casting sand filled the lower volume of the socket to a height of approximately 4 cm. Several possible model scenarios were considered in order to determine which most closely represented the conditions of the experimental test. One option was to leave the sand-filled interior surface unconstrained while fully constraining the surface above that as illustrated in Figure 4.2. This produced simulation results that varied widely depending upon the height of the unconstrained volume. In reality, the lower volume could not be considered as a void because the casting sand affected the stress experienced by the Duraform™ socket.

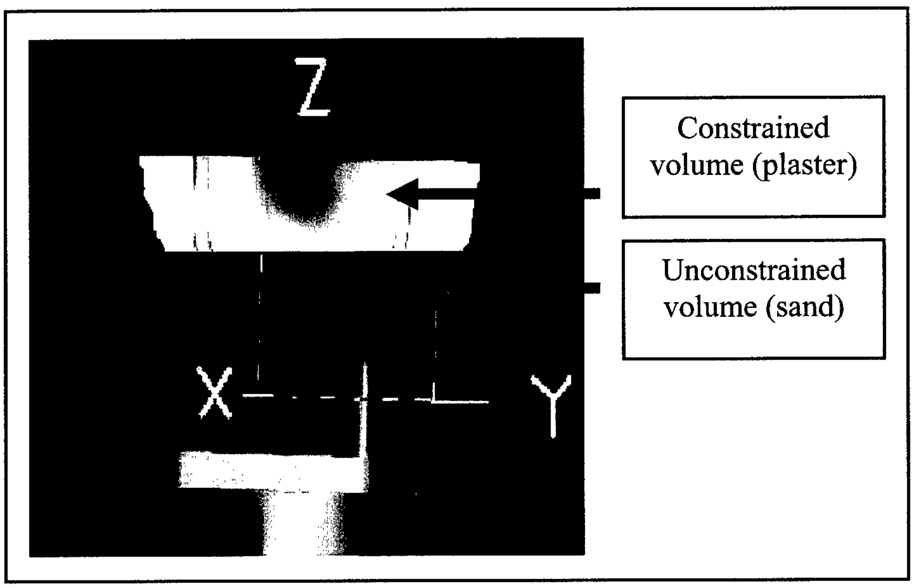

Figure 4.2

Possible option for constraining model to simulate effect of plaster and sand.

Simulating the properties of a dry, granular substance in compression presents additional difficulties. No simple parameters exist to effectively model these properties. The best solution available was to constrain the entire interior surface of the socket model in all directions in order to simulate the effect of the plaster and casting sand in the experimental test. By fully constraining the socket's interior, the effect of the plaster mold is achieved as closely as possible.

4.2 Analysis

The analysis used a 5mm mesh, meaning that no element had a dimension smaller than 5 mm. The elements were prescribed as parabolic tetrahedra, using 10 nodes per element. This resulted in a total of 66,197 nodes and 27,220 elements. A load of 159.9lb (711 N) was applied to the free end of the pylon such that the force vector concurred with the location and direction of the force applied to the free end in the experimental set up. The FEA force was applied to the entire circular surface of the pylon's free end. (Because the pylon is aluminum alloy and not susceptible to significant deformation under the low forces used, this application of force to the distal surface was essentially equivalent to a force vector applied at a point on the pylon surface.) Both the pylon and the attachment block were modeled as Aluminum alloy 1060.

The color key in Figure 4.3 indicates the level of stress experienced by areas on the model. The maximum stress for any element indicated by the analysis was 34.9 MPa in this simulation. The scale is automatically limited to the highest maximum stress experienced by any element, indicated in red. The only point on the socket that exhibits a high level of stress is approximately at the center of the compliance feature's curvature, where that feature touches the base of the socket.

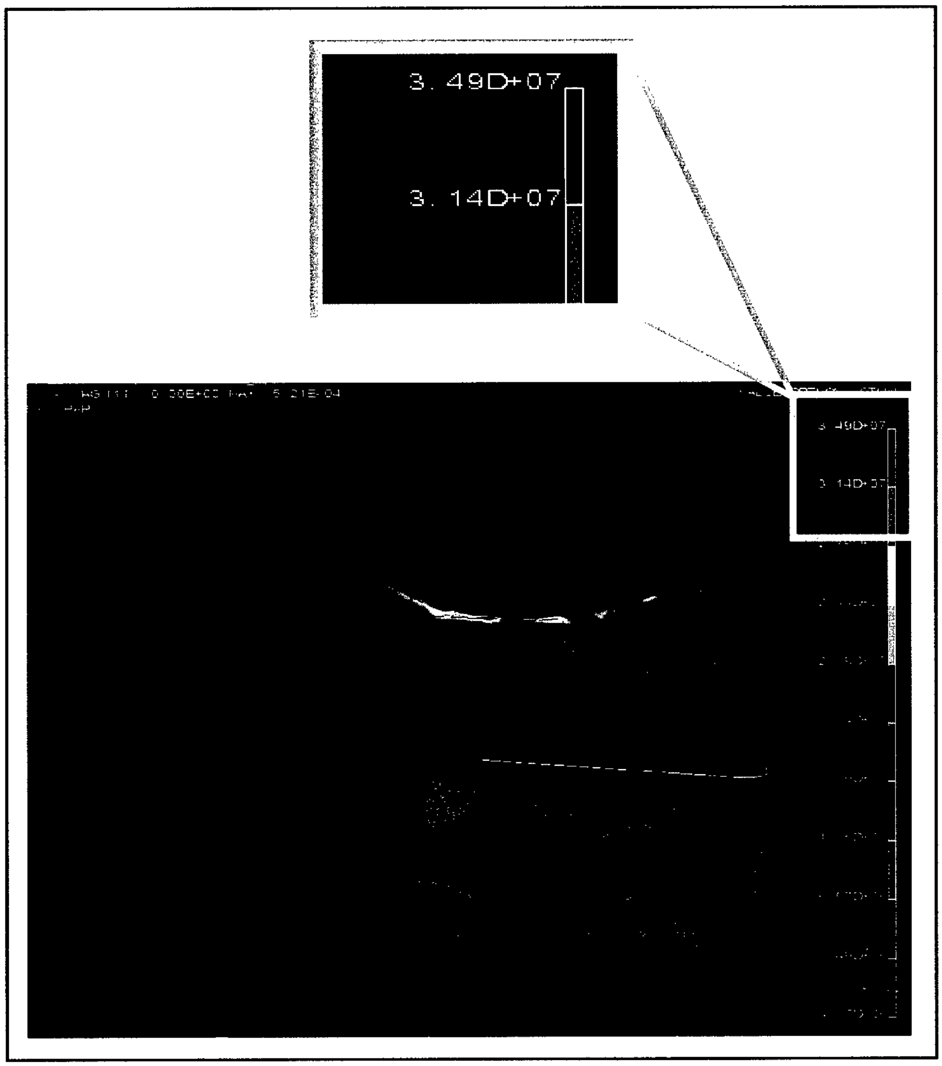

Figure 4.3

Results of analysis with maximum stress values and locations indicated.

In other simulations where the lower interior surface was not constrained, the points of greatest stress were also on the lower curve of the compliant feature. However, instead of a single, central point, the stress concentrations appeared as a pair of points, symmetrical about the center line of the compliant feature in the sagittal plane.

4.3 Comparison of Results

In the experimental test, the failure load was 159.9 lb for the gradually increasing load. Using this experimental failure load, the finite element analysis produced a maximum stress of 34.9 MPa. Based upon the published material properties of Duraform™ PA [2], the maximum stress experienced at the point of initial failure would be near 44MPa. This equates to a 20.7% difference between the FEA stress and the expected stress induced by a failure load.

Several factors influenced the FEA and may be logically considered as sources of the error. First, due to the fact that the complete interior of the socket was constrained, the plaster and the sand could not be differentiated. Also, the limitations of a FEA program should not be overlooked as each element represents a vast number of small particles. The maximum stress value is a close approximation but not an exact value.

Finally, the discrepancy between the two stress values may be attributed in part to the previously noted idiosyncrasy of Duraform™, in that its material properties are affected by the orientation in which it is formed. It would appear that the vertical layers used in the socket configuration do not optimize Duraform™'s load bearing ability. In fact, the FEA results only verify the need for a physical test in order to develop safe weight standards for the socket. Ideally, the test and FEA would indicate a maximum stress close to 44MPa and failure would occur at similar loads.

Despite these likely sources of error, a difference of 20.7% is a sufficiently accurate approximation to assert that the FEA concurred with the results of the experimental test. Also, the FEA was in agreement with the bending test in terms of the point of greatest stress. The analysis indicated a maximum stress value at the same location on the socket where the crack initiated during the bending test.

The FEA results do suggest that a greater load would be necessary to reach maximum stress levels and cause failure. The disparity between the two results leaves the value of the socket's failure load as existing within a range of values rather than a specific estimate. Additionally, the FEA results suggest a higher limit than the experimental test and therefore, cannot be considered conservative. The FEA requires further investigation before it may be considered a fully reliable tool for analyzing sockets without a bending test.

Summary

The FEA results were within a reasonable error range to be considered in agreement with the results of the bending. In this comparison, the bending test suggests a lower maximum loading than would be expected from the FEA alone. This seems to reaffirm the need for a shape-specific method of testing the socket and demonstrate the potential variation of stress properties for different build orientations of Duraform^{TM} parts. However, more bending tests should be performed and compared with appropriate FEA results.

Chapter Five: Conclusion

5.1 Interpreting Results

In order to provide estimates for safe weight limitations, it is important to consider what percentage of an individual's body weight is transferred into the horizontal component of the ground reaction force. One study examined the ground reaction forces for human walking and running [6]. For walking (1.25 m/s), the study measured a maximum horizontal force equal to approximately 28% of the body weight, as compared with approximately 125% for the vertical force component. As the motion studied for breaking the socket must be assumed to create an impact force greater than that experienced during normal walking, it is more representative to consider the data for a running individual. The force component percentages measured at a running speed (3.8 m/s) were approximately 275% of the person's body weight vertically and 30% horizontally.

Using the running horizontal force as a guideline, the socket tested in this study (sized for an individual weighing approximately 140 lb) should be able to withstand a horizontal force that is 30% of 140 lb, or 42 lb. Allowing for a safety factor of three, the socket should be able to withstand a maximum horizontal loading of 126 lb. Compared to the failure load measured at 159.9 lb, the socket appears to be well within the limits for a person weighing 140 lb. However, these calculations only consider the effects of a single statically applied load.

In interpreting the results of the test using the static loading, it is important to consider that, as noted in the difference between impact loads for walking and running, a greater velocity of a body with the same mass, creates a greater total force [6]. Therefore, the gradually increasing load, as applied in the bending test, would be a smaller total force applied than the reality of an individual landing with some measure of impact. It is important to note that the actual loading experienced by the socket is greater under impact than static loading for a given weight of an individual.

A general rule of thumb used for impact versus static loading is to assume the impact load would constitute a force double that of the static load. Using this estimate, the results should be compared to a load calculated as 140 lb * 30% * 3 (safety factor) * 2 (impact loading). This results in a static load of 252 lb, much higher than the bending test failure load. The results of the bending test (159.9 lb) only allow a safety factor of 1.9 when impact loading is considered and would suggest that some redesign is necessary. Finally, the effects of fatigue must be considered, and fatigue testing should be included in a comprehensive approach to determining safe usage limits.

5.2 Future Work

The bending test provided a good approximation of the real world scenario, but if the limitations of available testing equipment could be overcome to a greater extent, a more accurate simulation would be achieved. Specifically, the fact that no vertical components were included presents the problem of maintaining multidirectional constraint on the socket. Perhaps a contact surface with a greater friction coefficient than the foam rubber insert would reduce the slipping problem, but it would still distort the data if any slip did occur.

The equipment used in the bending test (MTS 810) was capable of applying only vertical forces. It is feasible that the socket might be positioned at a desired angle to simulate the desired force vector. However, the limitations of constraining the test fixture during testing present a source of potentially significant error. If a more versatile machine could provide controlled, measured force and displacement in a direction not limited to a single axis, the test would be a truer simulation of the actual ground reaction forces. However, assuming such equipment is unavailable, other options may yet exist for constraining the socket without resorting to the use of plaster or some other medium that affects the properties of the Duraform™ socket.

Another shortcoming of the test as a reproduction of the stepping down scenario is the lack of impact. Again, equipment availability plays a role in this aspect but the ideal test would include measurable impact forces. Finally, the best method for reducing the variations between FEA and the bending test would require a socket with tensile specimens sintered simultaneously from the same powder. A maximum tensile strength could be determined for that socket and compared to the maximum failure load with minimized room for error. This would allow a clearer view of the effect that the socket orientation has on the material properties of Duraform™.

In order to determine the safe loading limits of sockets using a FEA alone, further analysis is needed. The bending test should be performed on several sockets and the results compared to the respective FEA results. If the bending tests produce similar results while the FEA results still differ, then the FEA may be considered to contain sources of error. Possible improvements to the FEA include refining the mesh size, if possible, or examining ways to constrain the socket so that it more exactly matches that of the bending test.

The socket design performs reasonably well but certainly improved designs should be explored. The goal is to increase the durability of the socket for the type of loading explored in this work. The results of both the experimental test and the FEA point to a very specific region that incurs the largest stress values. This region is along the lower edge of the compliance feature as indicated with arrows in Figure 5.1.

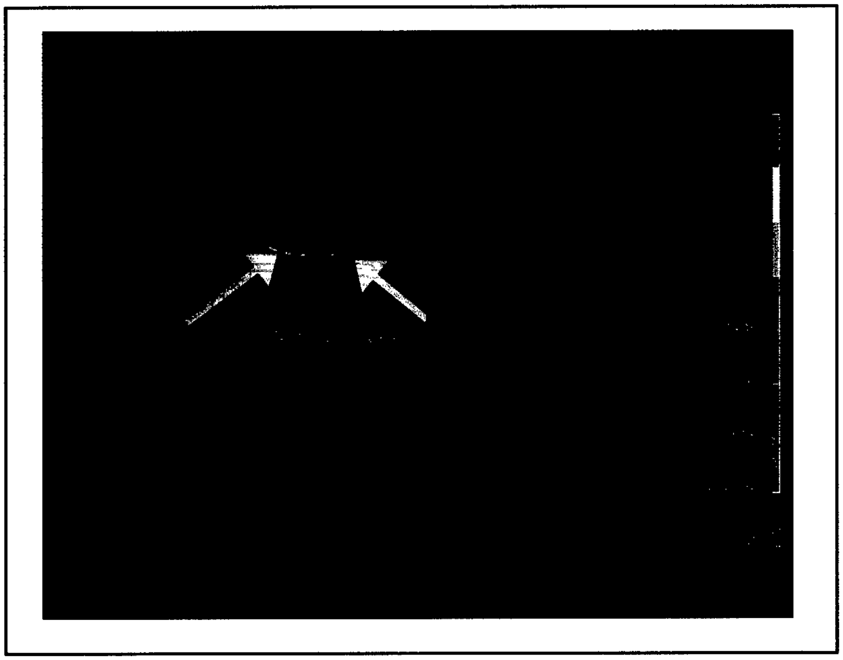

Figure 5.1

Finite element model with high stress points indicated.

The first step towards an improved design involves modifying the thickness of the socket wall at the compliance feature as this is where the socket failed and where the FEA indicated the greatest stress concentrations. It is not necessary to maintain a uniform thickness throughout the feature and a plausible solution would be to add filleting in the high stress region. Additional thickness is needed along the curve of the feature to avoid geometric discontinuities which create stress focal points. Ideally, this would equate to a larger force needed to reach the maximum stress value found in this analysis. An initial suggestion for this type of improvement is shown in Figure 5.2.

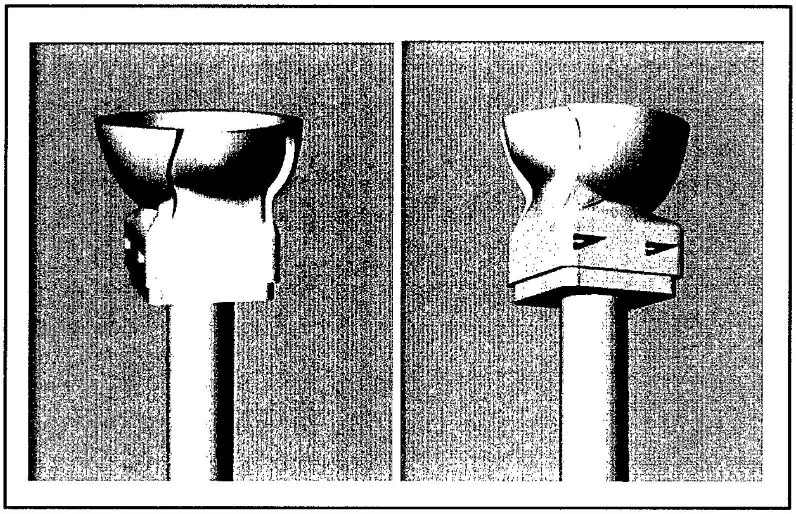

Figure 5.2
Modified socket design.

The optimal solution reaches a balance between improving the failure load of the socket and maintaining the benefits of the compliant feature. The aesthetic quality of the socket cannot be ignored, either, and the curved tapering of the lower portion of the socket should be preserved as much as possible.

The most effective approach would involve developing several prototypes of increasing thickness that push the limits of compromise with the compliant feature and aesthetic considerations. The bending test (either the one designed in this work or an improved version) and FEA should then be employed to determine which revised design returns the greatest increase in the failure load with the fewest drawbacks.

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