

AC 2008-1885: SOCIALLY RESPONSIBLE DESIGN PROJECTS IN AN UNDERGRADUATE ENGINEERING EDUCATION PROGRAM

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Socially Responsible Design Projects in an Undergraduate Engineering Education Program

ABSTRACT- *This work describes several design projects in an undergraduate engineering program which are directed to benefit an individual or a community. Examples of such projects are: 1) Feeding Device for people with disabilities. 2) "Fun" to operate water pump to be used in developing countries. 3) Exercise bicycle machine for people with Down syndrome. 4. Tooth Paste dispenser machine. 4) Design and analysis of an artificial Prosthetic leg. In this paper, however, only the design of artificial Prosthetic leg and its development is described in detail. The rest of the projects mentioned above are in development stage and they will be presented during presentation of the paper.*

Thousands of people world-wide currently require artificial leg prostheses. The basic design of a prosthetic leg consists of an axial structural member, a foot component, and a cosmetic cover. In the past two decades, prosthetic limb design has advanced significantly, with an emphasis on a very active lifestyle that includes sport activity as being one of the normal ones. As a result prosthetic technology has needed to improve to minimize subsequent injuries of the spine and other joints. The foot is required to simulate the shock generation and absorption properties of intact foot, store the energy from the early part of the stride and release it again at the point of take-off. Because of this, the requirement of the foot design is different and can be mathematically quite complex based on the chosen geometry, material and required performance. A wide range of different mechanical designs have been developed by number of companies and suppliers and there is significant room left for more investigation by the researchers.

This paper is primarily an undergraduate research level paper and its primary goal is to design and investigate improving such mathematically complex problem of artificial leg using the state of the art solid modeling and analysis technology available to students in an undergraduate education. The intent of the paper is to open the way to other undergraduate students to get involved in research early in their education and be able to choose their future career path more readily. A short introduction is gathered from the available literature about the mechanism and kinematics of human leg. A few designs similar to the ones already in existence is studied and investigated and a few more new designs are introduced and investigated using the most up-to-date software packages in solid modeling and Finite Element Method.

I. Introduction

Engineering and science education must take into account the social, economic and political contexts of their disciplines, help students develop new skills and interests and conduct undergraduate research. The engineering education of today must be motivating and interesting to get the students' attention. In essence, engineering and science based education today aims to prepare students to be successful in a changing workplace, be competitive and resourceful with new ideas and knowledge in use and application of new technology that the computers and software available in higher education in engineering. Coursework and classrooms must be up-to-date, collaborative, active learning environments and filled with new technology and ideas. Engineering graduates should be exposed directly to the "real-world" problems¹. The graduates should realize that a good portion of the engineering skills is dedicated to actually formulating the problem and asking the right questions, in addition to trying to find a solution. Today's industry demands a production-ready graduate, rather than a graduate who will still need some further training². We need to change some of our classrooms into innovation centers for small scale projects and ask the students to be the innovators of such projects. Industry needs young researchers and innovators who can save them money from the day they start working for them. In responding to this need to reshape our curriculum and programs to provide an undergraduate education for living and working in the technologically dependent society of the twenty-first century, undergraduate research is an important issue that the higher education of today needs to give a careful attention. One factor that will promote undergraduate research and development of students' process skills is the widespread use of multi-media and worldwide information networks. Internet is like a library that the old engineering graduates did not have available to them. Using the internet students can access new information and coursework, journal papers, conference proceedings, as well as interact with other students, researchers, practicing engineers and scientists in industry and government, and experts around the world. What is so called a "PC" has evolved in a serious computational and design tool for students in engineering. With the availability of fast computers and software for every subject, it is now possible to conduct high quality undergraduate research. Through the use of modern technology students will bring intuition and judgment for problems, which could not been possible in the old days. These tools can provide students the ability to analyze complex and practically applicable research projects in their undergraduate education. The new instructional technology is at the heart of what today's entering college students are familiar and comfortable³⁻⁴.

II. Artificial Prosthetic Leg

Many people around the world currently require artificial leg prostheses. The design of a prosthetic leg requires knowledge in human anatomy as well as engineering. In the past two decades, prosthetic limb design has advanced significantly, with an emphasis on a very active lifestyle that includes sport activity as being one of the normal ones. As a result prosthetic technology has needed to improve to minimize subsequent injuries of the spine and other joints. The foot is required to simulate the shock generation and absorption properties of intact foot, store the energy from the early part of the stride and release it again at the point of take-off. Because of this, the requirement of the foot design is different and can be mathematically complex based on the chosen geometry, material and required performance. A wide range of different mechanical designs have been developed by number of companies and suppliers and

there is significant room left for more investigation by the researchers. In this work, the research is conducted by an undergraduate mechanical engineering student on design and analysis of artificial prosthetic leg.

The legs carry all of the weight of human's body and they can be considered to be the most vital organs for human's mobility and comfort. An artificial leg must resemble the natural human leg in every way in order to be able to replace one. Thousands of human beings in many parts of world are in need of a lower leg replacement but they are unable to afford the high cost of current prosthetic components and designs. The people living in those parts of the world are forced to resort to crude imitations constructed from wood or bamboo without regard to comfort or safety. However, in the new age of technology and with availability of computers which contain software capable of massive computations for design, our young engineering graduates, can perform much more practical and applied research in the area of prosthetic artificial leg design and be able to help to reduce the cost of developing designs that are not affordable in many parts of the world.

Artificial leg design has been the focus of many researchers for the past many decades. Appold and Bennett⁵ found the loading on an above knee fiberglass socket by building the socket with pressure transducers. Bielefeldt and Schreck⁶ found the difference in loading of four different sockets, during the stance, which is a phase of a way of walking when part of the foot is in contact with the ground, for one patient. Stewart⁷ determined the load path of prosthetic socket using finite element analysis which allowed him to more accurately choose the socket linear frame and geometries. Saito et al.⁸ developed prosthesis made of fiber-reinforced plastic (FRP) which was comprised of an aluminum pylon, a cosmetic cover, and a constant cross-section composite foot into which aluminum supports are screwed to increase load-bearing capacity. Later Hahl et al.⁹ investigated experimental and numerical predictions of the ultimate strength of a low-cost composite transtibial prosthesis.

Using the 3D solid modeling (3DSM) and finite element method (FEM) a selection of sockets and foot geometry can be compared quickly with only computation costs which can be minimal compared to experimental one done on a physical model. Having the physical geometry and weight of the patient, the ground reactions can be calculated during walking. The hip forces then are applied for various conditions of the posture of the body to the 3D model and finite element used to come up with the best loading scheme. Using the loading scheme the socket material can be compared with various socket frames to come up with the most comfortable one. The requirements of the foot design are somewhat different. The prosthetic foot is required to simulate the power generation and absorption properties of intact foot and shank segments, store the strain energy from the early part of the stride and release it again at the point of take-off. This requires a special geometry for every patient because every patient have different manner of walking. In order the foot to save all the incoming strain energy it must be designed so that the foot to have exactly the same frequency that a patient's walking or juggling manners apply to the foot. For this reason one must design and tailor the foot for each patient differently. Composite materials offer flexibility in designing such demands for unique designs and therefore they would be the best choice for material.

III. Mechanics and Standards for Prosthetic Development

An artificial leg attempts to function like a normal leg. The artificial leg requirements are specified in the “Standards for lower-limb prosthesis”. The requirements for the joint mechanism are under structural part of these standards. However the function of “the lower limb assemblies and components shall approximate the anatomical counterparts in function and provide the types and ranges of motion to produce optimum performance and gait”⁷. The leg is required to support a static axial load of 2080 N in compression and an axial torque of 24.5 N-m. The leg must also be able to stand a dynamic force of 1060 N in compression and 12.5 N-m torque. The walking motion of a human is divided into two phases for each step. These are the stance phase and the swing phase. The stance phase takes 63% of the total time of a step. This value may vary for each patient.

Figure 1 below shows the knee mechanism⁷ and as it is seen the knee has to be free to swing yet locked during the stance phase. There are three classes of knee mechanisms with several types in each class. The first class is a free knee where the only limitation on rotation is from the friction of the bolt and bush assembly. The second class allows for adjustment of resistance to rotation. The resistance is either from mechanical friction or fluid damping. Class two is swing phase adjustable. Class three is swing and stance phase adjustable.

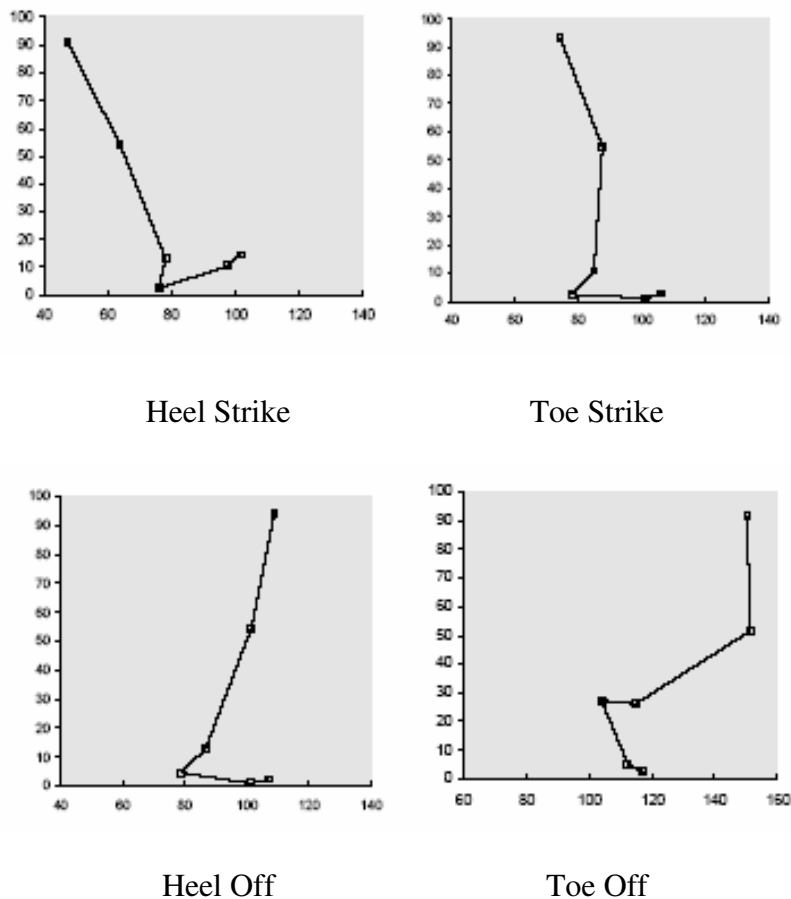


Figure 1. Human knee mechanism

IV. Design Models

First Model of prosthetic foot

The prosthetic leg consists of an axial structural member, a foot component, and a cosmetic cover. Figure 2 is a 3D solid model created in this work of a foot and axial member used by Hahl¹⁰.

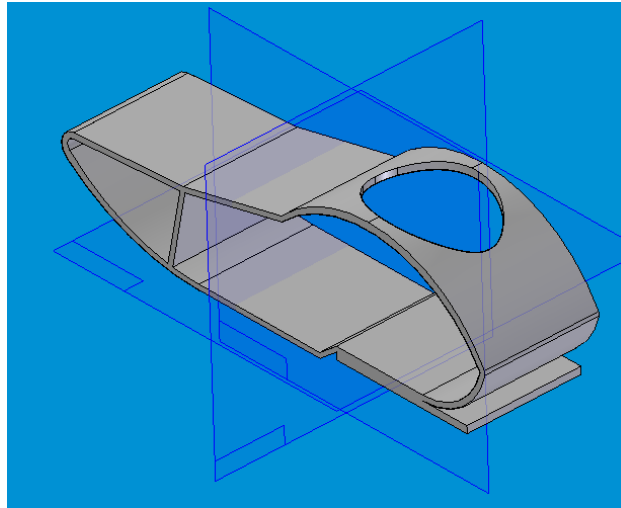


Figure 2: 3D Solid Model of the foot

The model used by Hahl was made of a simple 6061-T6-aluminum pipe as the axial member and the foot component was made out of FRP composite shell of constant cross section. The composite is made of a vinyl ester resin reinforced with E-glass fibers. Figure 3 shows the actual picture of the model used by Hahl and his experimental setup to calculate the principal stresses using strain gages.

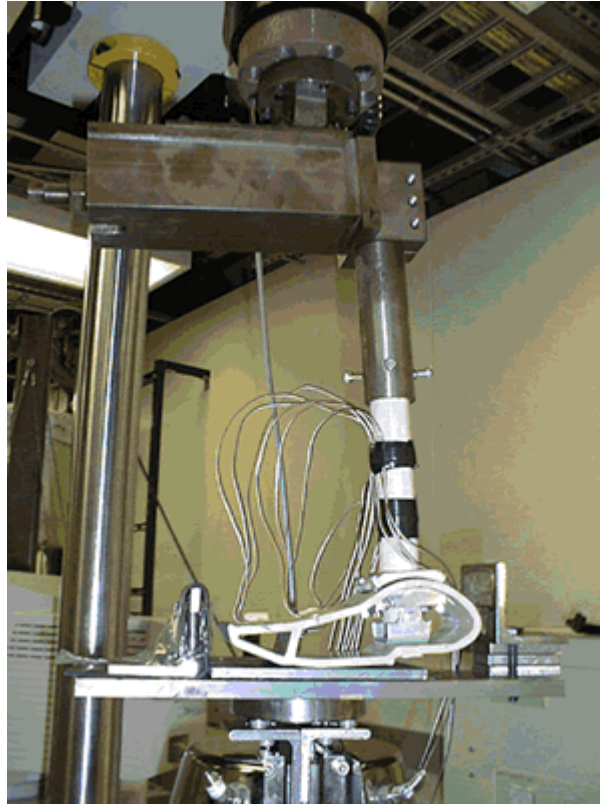


Figure3 Photograph of the setup used for mechanical testing of the prosthesis by Hahl ⁷

Theoretical Prediction of Failure Load on material with properties shown on Table 1 was performed by Hahl on the optimized design using the Tsai-Hill Failure Criterion.

Table 1

Values of lamina strengths for E-glass/vinyl ester with $v_f=30\%$

	S_L (MPa)	S_T (MPa)	S_{LT} (MPa)
Tension	584	43	44
Compression	803	187	64

Figure 4 represents the experimental test graph of load *versus* displacement, Hahl obtained, as the prosthesis was loaded. A distinct system of cracks was seen in the base of the stiffener section at a load of 6,600 N. Figure 5 (a) and (b) are photographs of the crack, taken during testing at applied loads of (a) 6,600 and (b) 7,000 N. The onset of the crack occurred at the midline of the thickness of the foot (2.5 mm) at the base of the stiffener. It can be assumed that the crack was caused by interlaminar failure at a load of 6,600 N. Table 2 is a summary of the failure loads for the original prosthesis and the optimized design.

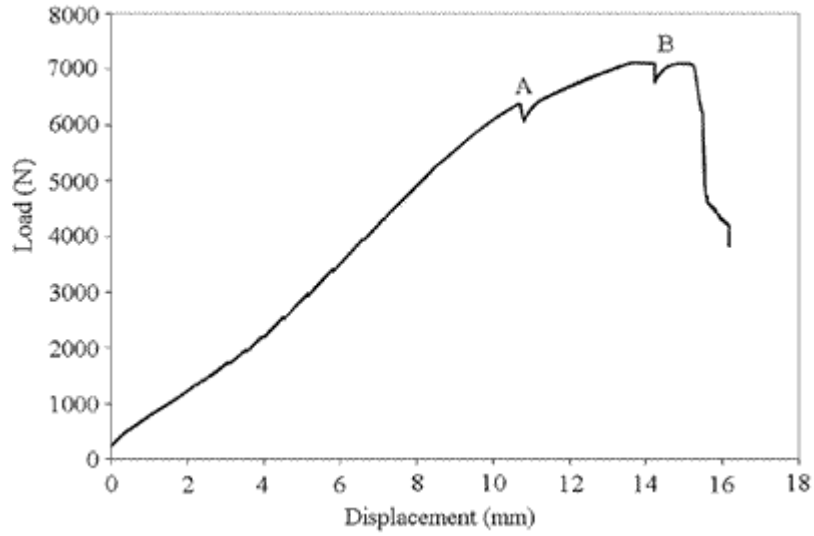


Figure 4 Load versus Displacement as the prosthesis was loaded in compression.

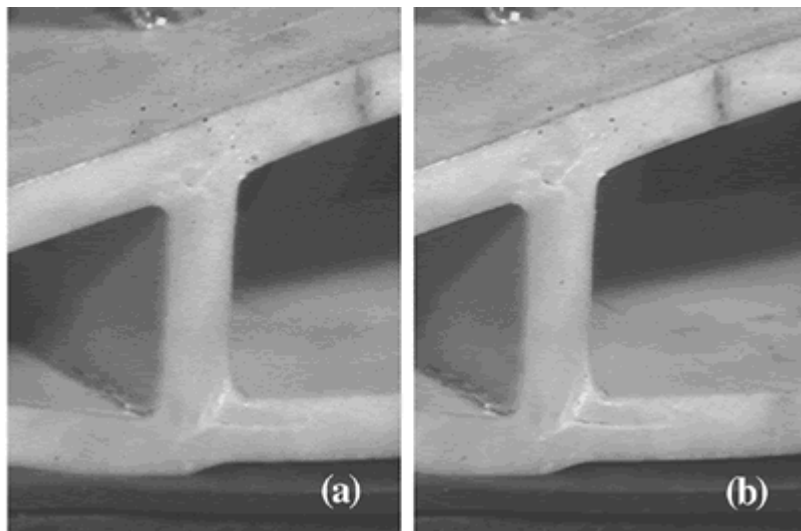


Figure 5 Photograph of the cracking in the stiffener section of the composite foot at loads of (a) 6,600N and)b) 7,000N.

Table 2

Summary of experimental failure loads.

	Optimized Design	Original Design*	ISO Requirement
Failure Load	7,000 N	5,500 N	3,200 N

Figure 5 presents the imported model of the foot created by the authors into ANSYS, Finite Element Analysis software. This model can easily be analyzed for displacements as well as

failure at the weak spots. Most importantly, model analysis can be performed to investigate the energy absorption as well as vibration performance of the foot under different conditions.

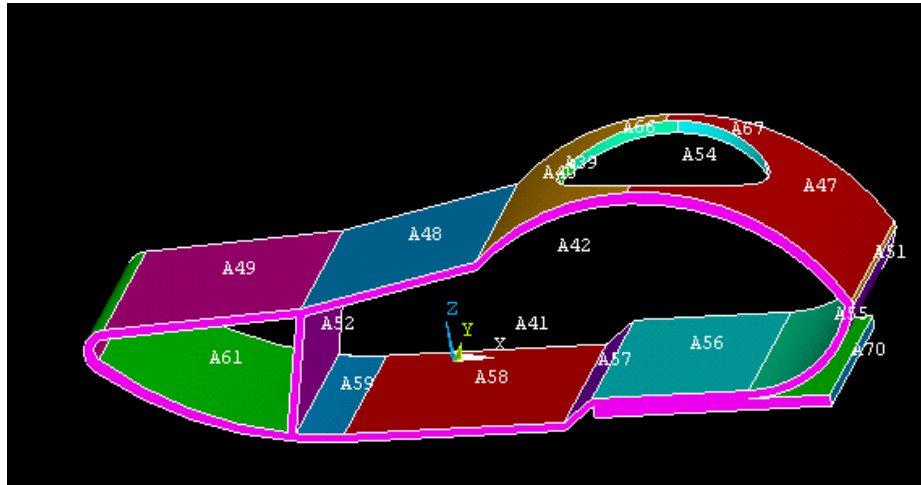


Figure 5 Redesign of a prosthetic foot for analysis in ANSYS

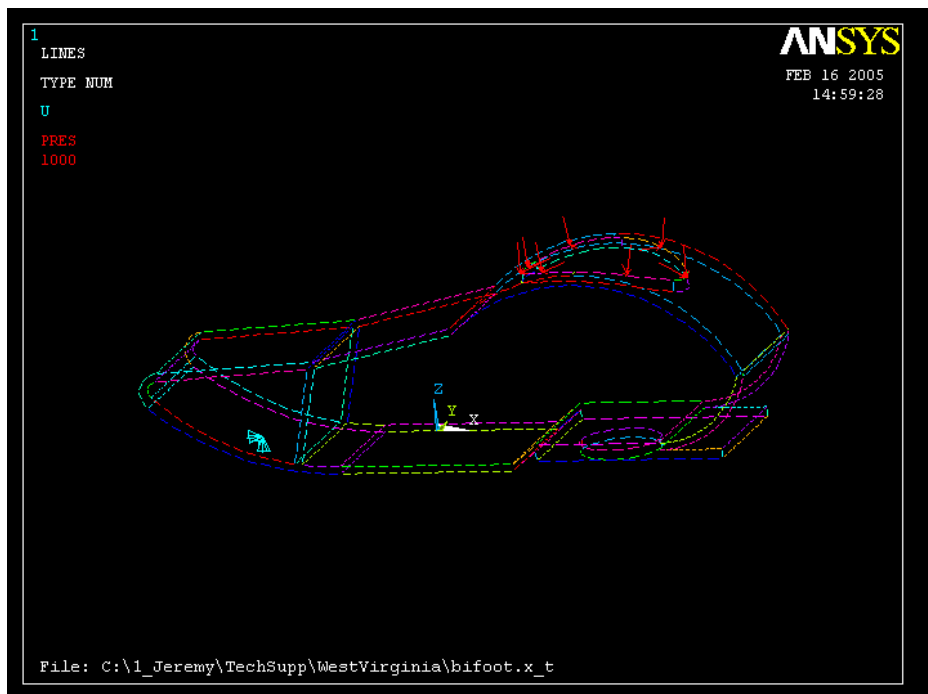


Figure 6 the foot under loading in ANSYS

New suggested models of prosthetic foot

During the process of prosthetic development, many aspects go into the modeling, material, and stability of the design. In the human body, there exist vibrations caused by the motion of the body. These vibrations, like the ones found in structures, must coincide with one another to produce a working system of motion. These vibrations must be matched in the prosthetic to ensure the system is not flawed, so as to mimic the exact working system that existed before the

loss of the limb. If the prosthetic is not designed properly, the vibrations that occur from walking, running, and other physical activities will damage the entire working system. This flaw in the vibration stability can cause loss of cartilage in the bone joints, as well as the compression of other bones such as the spinal cord. For these reasons, the development of the prosthetic must be looked at thoroughly leaving no factor unchecked. The foot, itself, is normally contacted at three key points, the back of the foot, the ball, and the toes. As a person walks, they lift their leg and as the foot hit the ground, the back of the foot touches, placing the persons' weight on this one area. The foot then comes down and the force is shared with the front of the foot and then, finally, the foot bends placing the weight amongst the toes. Utilizing this idea, manufacturers have tried to recreate this motion by using bendable metals and geometric configurations. The most common configuration is to design the back of the foot with a curve. This helps simulate the vibrations caused by the body. A slight curve is then placed moving from the back to the front to simulate the "rocking" motion performed when walking. Once these designs are created into a model, the prosthetics is made and subjected to a rigorous testing plan. The foot is connected to a machine where it is supplied with a force and different motions to find the key stress points in the design. This process can cost hundreds of thousands of dollars and months of testing. Through the use of Finite Element Method and software programs to carry the calculations, such as ANSYS, these same stresses can be found in a fraction of the time. This gain in development time will allow the engineers to find the flaws quickly, as well as having more time to improve the design and create an endless amount of design configurations. Along with this, the decision on the material for the item can be investigated as well. The latest programs offer the ability to choose from a wide assortment of materials to be used on the product and contain the information for each material such as the modulus of elasticity and poisons ratio. The most important part in using this program would be its animation capability. This function allows the designer to apply forces in the places he/she desires and can watch the object move as it would in real life.

Based on the factors mentioned above in creating new models for a prosthetic human foot, many different models have been created in this work. Some of these models are shown in Figures 7 through 10. The models are created based on size of an average human foot having comfort and perform better under different loading conditions. For example, the model shown in Figure 7, is created based on the idea that the foot needs to be light and strong to perform well under high running speeds of the amputee. The curvatures in this model are designed to improve the comfort transferred to the leg during such harsh conditions.

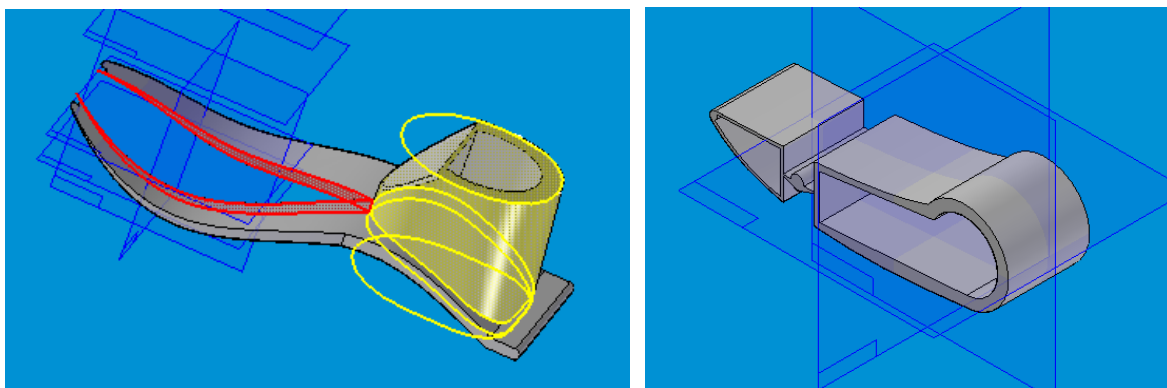


Figure 7 Solid Model for second Model

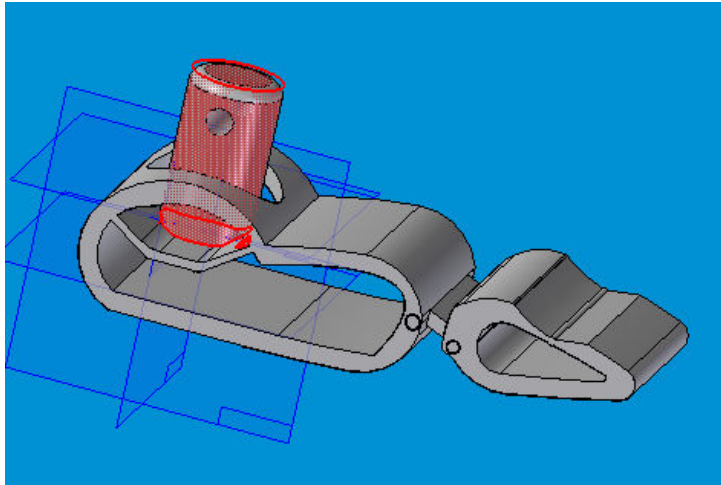


Figure 8 Solid Model of Third Model

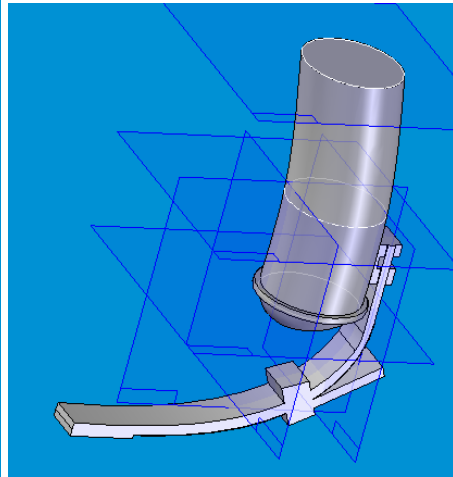


Figure 9 Solid Model of Fourth Model

Figure 10 Solid Model of Fifth Model

Modal Analysis

Modal analysis has been performed on the model shown in Figure 10. This model is designed for an athletic amputees and the performance of the leg as well as the foot component is under investigation. Figure 11 shows the meshed model of the whole assembly ready to be loaded under conditions of weight and running. However, since the foot part of this assembly will undergo most vibration, it is separated from the assembly for further modal analysis.

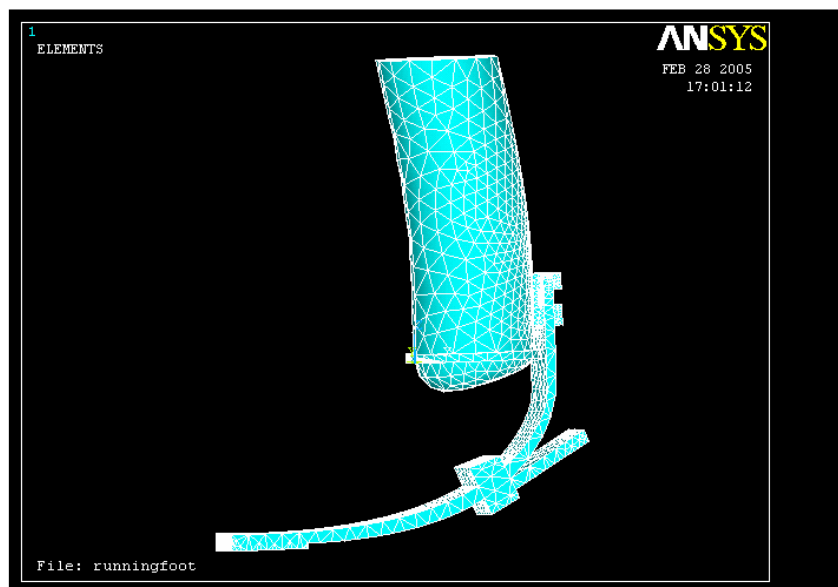


Figure 11 Prosthetic leg model meshed with 10 noded tetrahedral elements in ANSYS

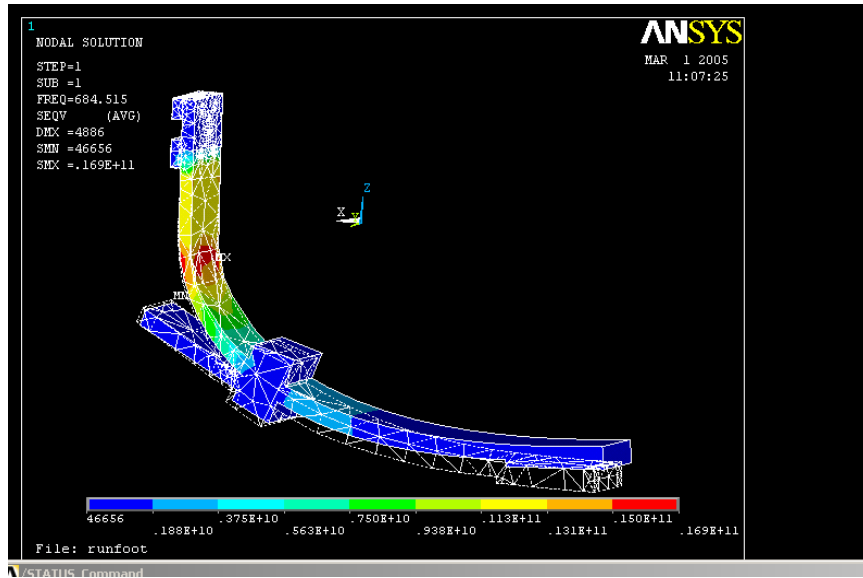


Figure 12 First Mode shape of the foot assembly with natural frequency of 684.5 Hz

Up to 10 frequencies and mode shapes for this model have been extracted from the modal analysis. The results of the mode shapes and frequencies reveal satisfactory results.

V. Conclusion

In this paper the implementation of recent analysis and solid modeling tools in undergraduate research has been presented. Modeling and analysis has been obtained successfully in design of artificial prosthetic foot by an undergraduate student. Reforming undergraduate education in engineering is necessary in order to convince the industry that what we teach is likely to be used in their practices. The National Research Council (NRC) wrote: “(University) curricula as a whole lack the essential interdisciplinary character of modern design practice and do not teach the best practices currently in use in the most competitive companies.” The NRC is referring to the outdated and sometime irrelevant nature of the undergraduate engineering education which places a low market value on teaching¹¹⁻¹². There are many more compelling reasons for promoting undergraduate research and introducing students to new topics early in their education, one of them being the desperate need for financial support for research and development at universities.

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