Comparison of Shear Stress Acting in the Sockets of Typical Mobile and Immobile Ankle Prostheses Using Finite Element Analysis (FEA)

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Abstract

Major problems with below the knee prosthetics today involve both cost and mechanics. Current design lacks an ankle complex which disrupts not only the natural biomechanics of ambulation but also sitting. Without the necessary frontal plane motion (inversion and eversion) along with sagittal plane motion (plantarflexion and dorsiflexion), the current manual immobile prostheses for below the knee amputees the lower limb is unable to adapt appropriately to certain ground surfaces because they are rigid and do not allow for a normal gait. Therefore this causes excessive moment and shear force to occur and consequently compensation occurs at the stump and socket interface. This will later in turn cause complications of pressure sores and discomfort along the stump. In the biomechanics lab at Mercer University, students have been involved in several research projects and lab works relating to lower extremity biomechanics using gait analysis system and measure moment and reaction forces.

The authors used Pro-E to model a mobile (full range of motion at the ankle level) and immobile (rigid and no motions occur at the ankle joint) prosthetic devices and analyzed the shear stress in the pylons and sockets with a constant body load of 1,000 lbs acting in the sockets. Aluminum is selected for the material property of the pylon and the socket. Results showed that the Von Mises stress to anterior aspect of the immobile ankle prosthesis was 1,567 psi compared to 131 psi for the mobile ankle prosthesis; the maximum shear stress acting on the immobile ankle prosthesis anteriorly was 905 psi verses 52 psi in mobile ankle prosthesis. The results also showed large amounts of reduction in stresses in lateral, medial, and posterior aspect of the mobile ankle prosthesis.

1. Introduction

With advancement in gait analysis equipment, students at Mercer University School of Engineering (MUSE) have been using biomechanics lab to learn and conduct research studies focusing to lower extremity biomechanics. Students have learned the gait of the limb length discrepancies, valgus verse varus deformity, normal verse below knee amputation (BKA) prosthetic walking gait, and rigid verse flexible ankle prosthetic walking gait. Based on the results obtained from the gait analysis for ankle motions involving shear stress, developed in the sockets of mobile ankle and rigid ankle prostheses, authors of this paper used Finite Element Analysis (FEA) to compare the shear stresses acting on these sockets of the rigid ankle and mobile ankle prostheses.

Prosthetic ankles should capture the natural motion of the human ankle in order for below-the-knee amputees to experience as normal gait as possible. Though currently there are ankle devices that mimic the human ankle quite well, these advanced prosthetics utilize electrical parts, making them very expensive. Moreover, the ankles that do not cost quite as much are rigid and cause friction problems around the stump and socket interface, which results in infectious sores called decubitus ulcers around this area. Thus, designing a manual prosthetic ankle with natural range of motion is crucial role for prosthetic experts and biomechanical engineers.

2. Background

Amputation is the removal of a body extremity by trauma or surgery and the three main causes of amputations are disease, accidents, and birth defects. Below the knee amputations (BKA) are the most common type of amputations in the United States, inflicting over 200,000 Americans nation wide. Below the knee (trans-tibia) amputations are preferred over above the knee amputations because the knee joint is left intact. Figure 1 below shows a frontal and medial view of the residual limb (stump) of a BKA[1].

Figure 1. Frontal and medial x-ray views of BKA stump

The importance of random motion in the ankle joint is enormously important while walking, standing, or climbing stairs. The functional anatomy of the ankle joint consists of four main movements (Figs. 2 and 3) that contribute to the random motion of the joint. These movements are dorsiflexion (motion of the ankle that raises the forefoot from the ground, occurs in sagittal plane); plantar flexion (motion of the ankle that raises the heel from the ground occurs in sagittal plane), eversion (motion of the ankle in the bottom of the foot moves towards the midline of the body and occurs in frontal plane) and inversion (motion of the ankle in the bottom of the foot moves away from the midline of the body and occurs in frontal plane).

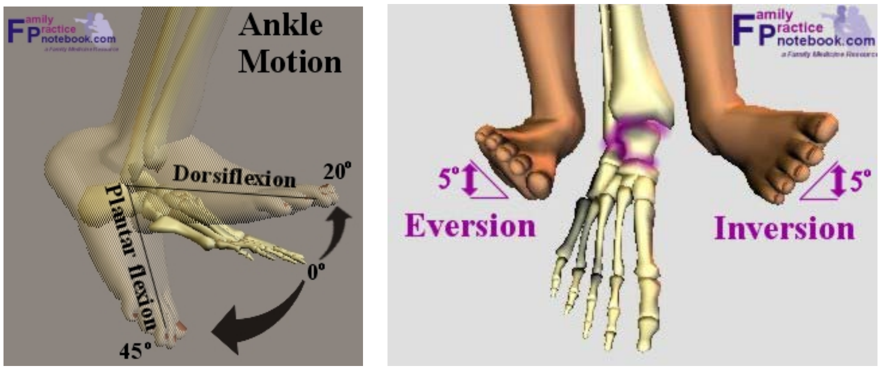


Figure 2. Dorsiflexion and Plantar flexion of the ankle joint are shown in the picture on the left. Eversion and Inversion of the ankle joint are shown on the right[2]

The sagittal plane and the frontal plane divide the body into components. The sagittal plane divides the body into left and right halves, the frontal plane (coronal plane) divides the body into anterior and posterior halves, and the transverse plane divides the body into upper and lower halves. Figure 4 shows the three planes that divide the body into sections.

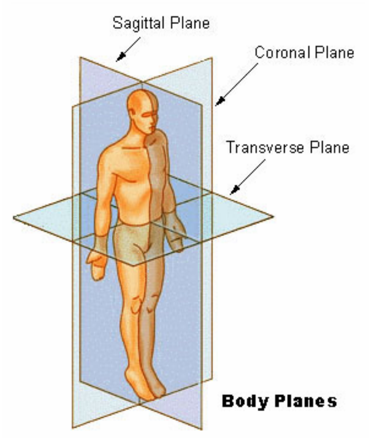


Figure 3. The human body planes[3]

For the many BKA sufferers faced with this life altering difficulty, prosthetic devices worn in place of the removed limb will serve to drastically improve the amputee's chances of returning to normal daily activities[4]. If the prosthetic device that the BKA wears does not allow for motion in the ankle joint, then friction can occur between the residual limb of the amputee's leg and the socket of the prosthetic device. This friction can lead to decubitus ulcers which can cause infection and in rare cases even death.

Decubitus ulcers are lesions ranging from redness of the skin to ulcers with necrosis (death of cells and living tissues) of the skin, fat, muscle, and bone[5]. Another word for the term decubitus ulcer is pressure sore or pressure ulcer. These ulcers can breakdown the skin and make it vulnerable to infection. These ulcers often lead to hospitalization, plastic surgery, and further amputation and can cost thousands of dollars to treat. Decubitus ulcers form over weight bearing bony prominences and are a result of frictional forces at the residual limb-socket interface[6]. Frictional forces act parallel to the skin surface and produce shear strains within the skin and underlying tissue. These forces are present whenever there is sliding of the tissue over a surface and they are higher when tissues between bone and skin are thin. Figure 4 shows a decubitus ulcer in a diabetic BKA. (The decubitus ulcer: many questions but few definitive answers).

Figure 4. Decubitus ulcer on the residual limb of a BKA

3. Materials and Methods

Three-dimensional (3D) models of rigid ankle prosthetic (Fig. 5) and mobile ankle prosthetic (Fig. 6) devices were developed using Pro- Engineer Wildfire 2.0. The 3D Pro-E models were analyzed using the finite element analysis (FEA). The standard Pro-E branch rendered the solid model of the full below-knee prosthetic leg. Through static loading, Pro-Mechanica, another branch of Pro-E, facilitated a stress analysis on the mobile ankle 3-D prosthesis model; Figures 7 and 8 shows the 3-D model of the prosthesis with rigid ankle and mobile ankle respectively. Analyses on the socket as well as the multi-axial compression rod determined the effects of shear stress and compression in these areas.

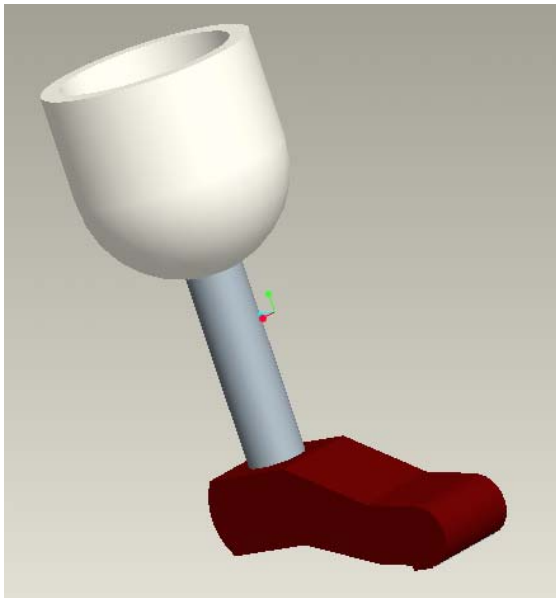


Figure 5. Typical Rigid BKA Prosthesis
(no motions occur at ankle joint)

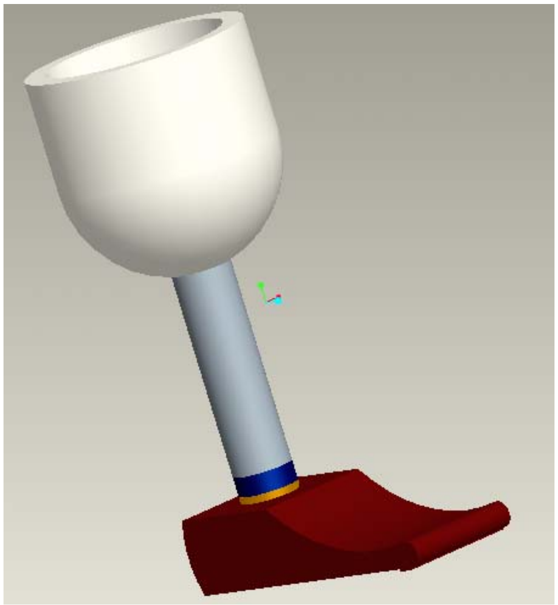


Figure 6. BKA Prosthesis with Mobile Ankle
(motions occur at ankle joint)

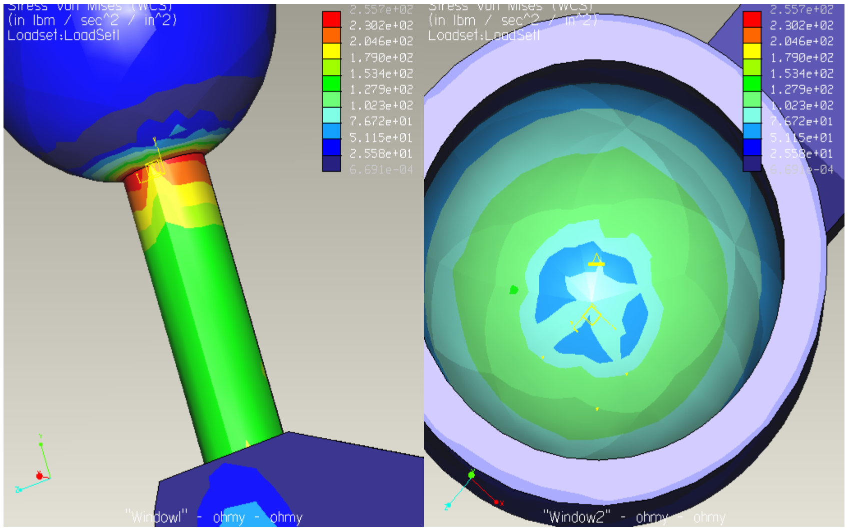


Figure 7. Static stress applied superiorly on the socket of the rigid ankle prosthesis: Anterior view with prosthetic device on plantar flexion (forefoot loading) of socket-shank interface and inner surface of socket, respectively

The primary goal of this study is to compare the shear stress in the residual limb-socket interface, between the rigid and mobile ankle joints of the below knee amputation prostheses. Conducting a shear stress analysis on this area allowed the authors to determine if flexibility in the ankle minimized the stress in this contact area. A flexible ankle tries to redistribute the loading from an obstacle in the pathway of the walker. Having this flexibility in BKA prosthesis would relieve the pressure around the residual limb-socket interface.

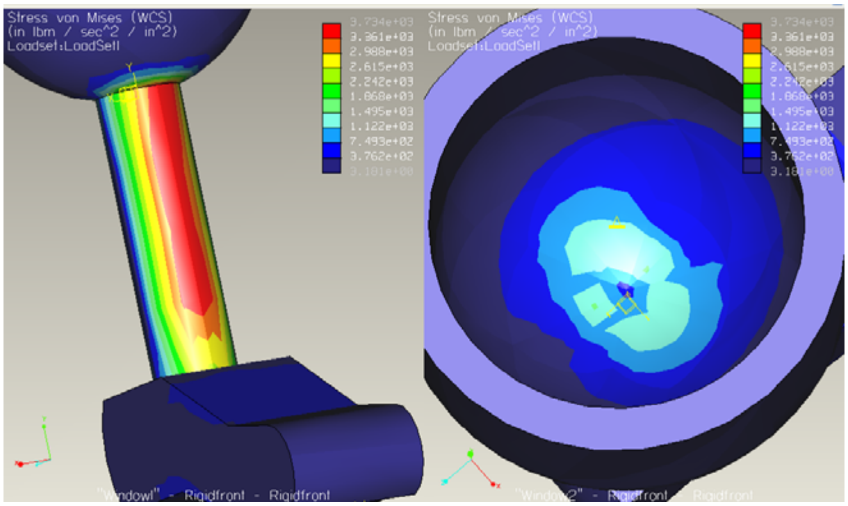


Figure 8. Static stress applied superiorly on the socket of the mobile ankle prosthesis: Anterior view with prosthetic device on plantar flexion (forefoot loading) of socket-shank interface and inner surface of socket, respectively

To consider the effects of a mobile ankle joint in a simple static analysis, the authors applied loading to different parts of the foot including forefoot, midfoot, lateral/medial sides, and a distributed loading to the rear foot (heel) area. The distributed loading represented the mobile ankle (flexible). The individual loading represented the rigid ankle not being able to move or redistribute the loading. The student team then compared the stresses around the residual limb-socket interface to determine if distributed loading caused lesser stress than the individual loading. Moreover, since the compression rod of mobile ankle must compress no more than one centimeter, an analysis on the rod allowed the team to observe its displacement from full body loading, while the rigid ankle prosthesis has no displacement on its rod.

The multi-axial compression rod was treated as stationary as well. The primary function of the rod is to efficiently withstand loading by compressing. Proving that flexibility in the mobile ankle minimizes the stress around the residual limb-socket interface suggests that a 'movable' rod will add to the flexibility of the ankle unit. Thus, both the cushion (polyurethane) located between the rod and the foot and the multi-axial compression rod of the mobile ankle were assumed to be stationary.

The socket for these prostheses had an 'estimated' diameter of 15 centimeters and a length of 20 centimeters. The 'diameter' as well as the length was estimated because the socket is fitted to the unique residual limb of the BKA. The prosthesis also used a 20-cm long shank with a diameter of 3 centimeters. For the stress analysis concerning the residual limb-socket interface, a uniform force of 1,000 lb in the positive y-axis was applied individually to different areas as well as to the entire heel area. Figure 9 shows a view of the Pro-Mechanica model, including the axis as well as the position of the loadings and the constraint. A constraint was placed on the top surface of the socket. For the compression rod analysis, the bottom surface of the compression rod was constrained. In addition, the top surface of the shank was loaded uniformly with a 1,000 lb-force in the negative y-axis.

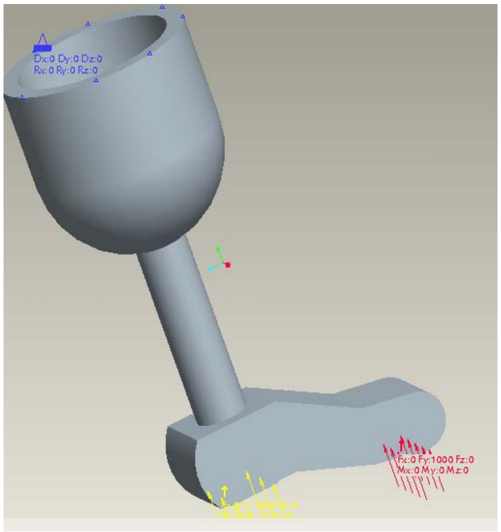
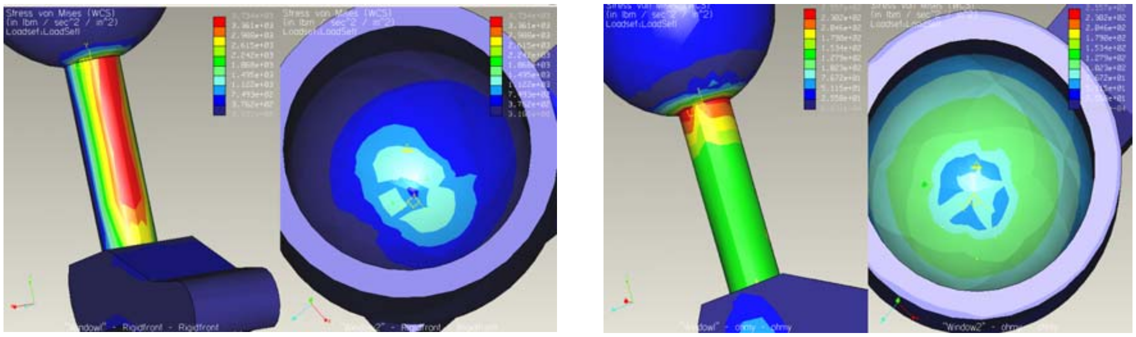


Figure 9. Pro-Mechanica view of prosthesis, showing axis, distributed loading, one of the individual loadings, and constraint

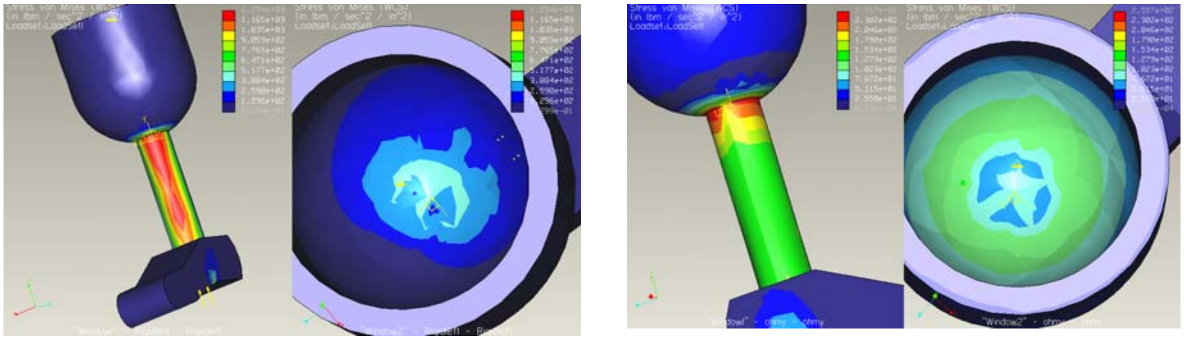
4. Results of Finite Element Analysis

The color variation of stress regions in the resulting images evaluated the evident stresses. A range of colors represented the stress levels, from blue regions, indicating lower stress levels, to red regions, indicating higher stress levels. Figure 10 describes the views of prosthetic devices on plantar flexion using Figure 7 as 10 B (rigid ankle) and Figure 8 as 10 A (mobile ankle) which experienced much more stress in anterior pylon (similar to normal tibia on plantar flexion) and less stress in the inner socket than the rigid ankle (Fig. 10A). Figures 10-13 compare the resulting images of the overall *von Mises stress*. These images show the stress concentration levels around the residual limb-socket interface and about the socket-shank interface. Superior Prosthetics recognized a significant difference in color variation between the distributed loading and individual loading. Images of the distributed loading demonstrated lower color (or lower stress) regions. Corresponding Tables 1-4 compare the distributed loading and individual loading in five stress areas: von Mises, maximum principal, maximum shear, σ_{xy} (stress in the xy plane), and σ_{yz} (stress in the yz plane).



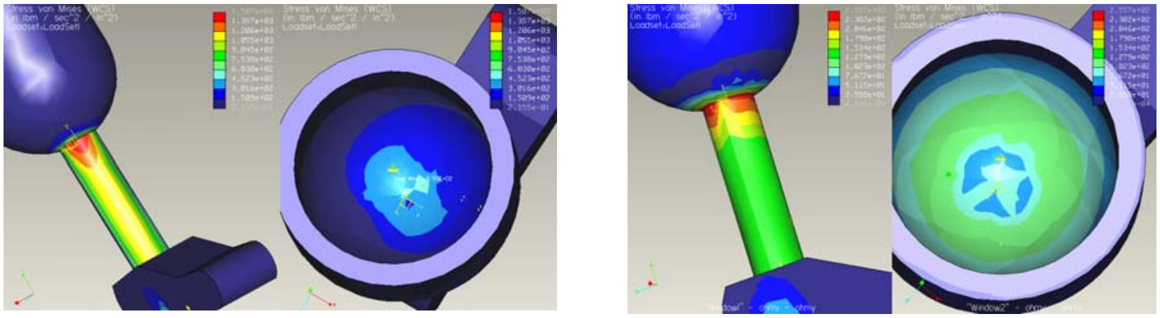
A B

Figure 10. Anterior views with prosthetic device on plantar flexion (forefoot loading) of socket-shank interface and inner surface of socket, respectively: A: mobile ankle, and B: rigid ankle



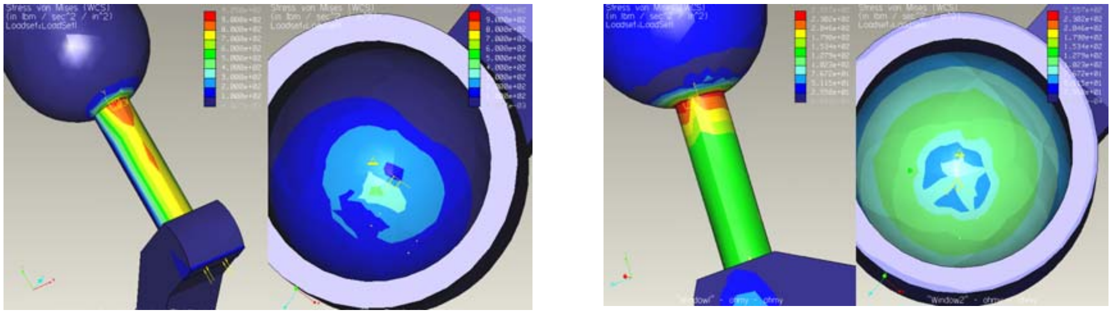
A **B**

Figure 11. Medial views with prosthetic device on eversion (medial foot loading) of socket-shank interface and inner surface of socket, respectively: A: mobile ankle, and B: rigid ankle



A **B**

Figure 12. Lateral views with prosthetic device on inversion (lateral foot loading) of socket-shank interface and inner surface of socket, respectively: A: mobile ankle, and B: rigid ankle



A **B**

Figure 13. Posterior views with prosthetic device on dorsiflexion (rear foot loading) of socket-shank interface and inner surface of socket, respectively: A: mobile ankle, and B: rigid ankle

Based on the results presented in Tables 1-4, the distributed loading had the lowest values for each stress area. The values of the distributed loading for the von Mises and the maximum shear were significantly lower than the stress values of the individual loading. According to the previous images and the results, the distributed loading, or the flexible ankle, reduced the stress around the residual limb-socket interface.

Table 1. Maximum stresses inside the inner surface of the socket with forefoot loading (*psi)*

Ankle Type	Von Mises	Maximum Principal	Maximum Shear	σ_{xy}	σ_{yz}
Rigid Ankle	1567	1738	905	241	231
Mobile Ankle	131	88	52	53	73

Table 2. Maximum stresses inside the inner surface of the socket with medial foot loading (*psi*)

Ankle Type	Von Mises	Maximum Principal	Maximum Shear	σ_{xy}	σ_{yz}
Rigid Ankle	551	649	317	124	110
Mobile Ankle	131	88	52	53	73

Table 3. Maximum stresses inside the inner surface of the socket with lateral foot loading (*psi*)

Ankle Type	Von Mises	Maximum Principal	Maximum Shear	σ_{xy}	σ_{yz}
Rigid Ankle	501	534	284	103	129
Mobile Ankle	131	88	52	53	73

Table 4. Maximum stresses inside the inner surface of the socket with rear foot loading (*psi*)

Ankle Type	Von Mises	Maximum Principal	Maximum Shear	σ_{xy}	σ_{yz}
Rigid Ankle	925	503	267	77	180
Mobile Ankle	131	88	52	53	73

5. Conclusions

The mobile ankle of the BKA prosthesis experienced much lower stresses in the interface between the stump and the socket in terms of Von Mises stress, maximum principle stress, maximum shear stress, shear stress in xy plane, and shear stress in yz plane. This study recommended that motions of ankle joint is needed to preserve in order to prevent distal stump pressure sores and ulcerations. Future studies of the authors include developing simulation models to the current manual BKA prosthetic devices and compare the stresses between them.

The results from this study will be used in teaching a new theory course and a lab course in biomechanics and the gait analysis of the below knee amputee. In the theory class, students will model a rigid and mobile ankle prosthesis using Solidworks, Pro-E, or ANSYS to simulate the human ankle motions in order to prove the mobile ankle motions are similar to the natural motions of the human ankle. In the lab, students will analyze the stresses in the inner sockets of rigid and mobile ankles (applying compressive and flexural loading) using the material testing system (MTS) available in the Mechanics of Materials Laboratory at Mercer University.

References

[1] Scott M., Ankle Anatomy, Family Practice Notebook.com, 2008

[2] Muilenburg, A.L., and Wilson, Jr., A. B., A Manual for Below-Knee (Trans-Tibial) Amputees, 1996 Retrieved July 14, 2007 from http://www.oandp.com/resources/patientinfo/manuals/7.htm.

[3] Yachigusa R., Wandering Around Martial Arts, Samurai, A Dojo, Nov. 30, 2006. www.yachigusaryu.com/blog/archive/2006_11_01.

[4] Sokolowska, A., Below-Knee Amputations, Retrieved July 15, 2007 from http://www.podiatry.curtin.edu.au/encyclopedia/bk_amputation/

[5] Dan R. B., and David, M. B., Are All Pressure Ulcers Result of Deep Tissue Injury? A Review of the Literature, Ostomy/Wound Management, Volume 53, Issue 10, Oct. 2007.

[6] Parsih, L., Peter L., and Joseph W., The Decubitus Ulcer: Many Questions But Few Definitive Answers, Retrieved September 21, 2007 from Clinics in Dermatology.

Biography

Ha Van Vo: Dr. Ha Van Vo is an Assistant Professor in the Department of Biomedical Engineering and Physician, Mercer University, Macon, GA. His main teaching and clinical research focus on sport medicine biomechanics, accidental injury biomechanics, rehabilitation engineering, medical devices, laser guide for surgery, orthopedic implants, and biomedical materials.

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R. Radharamanan: Dr. R. Radharamanan is a professor in the Department of Mechanical and Industrial Engineering at Mercer University in Macon, Georgia. He has thirty five years of teaching, research, and consulting experiences. His previous administrative experiences include: President of International Society for Productivity Enhancement (ISPE), Acting Director of Industrial Engineering as well as Director of Advanced Manufacturing Center at Marquette University, and Research Director of CAM and Robotics Center at San Diego State University. His primary research and teaching interests are in the areas of manufacturing systems (CAD/CAM and Robotics), modeling and simulation, quality engineering, and product and process development. He has organized and chaired/co-chaired five international conferences on CAD/CAM, Robotics and Factories of the Future, and organized and chaired one regional seminar on Operations Research. He has received two teaching awards, several research and service awards in the United States and in Brazil. His professional affiliations include ASEE, IIE, ASQ, SME, ASME, and ISPE.