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EXPERIMENTAL AND NUMERICAL ANALYSIS OF BELOW KNEE PROSTHETIC SOCKET

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ABSTRACT

People with special needs who wear prosthesis lower limb which is artificial device using to replace for missing body part. This work involved two major parts, the first part beginning with manufacturing of the prosthetic socket from composite material (3pyrlon,3carbon,3pyrlon), the patient case study is man with (85kg, 23 year, suffer from amputation below the knee of his right limb, the amputation occurs due to trauma accident). The GRF test is needed to determine the ground reaction force subjected on the patient foot. Also, F-Socket test is done to measure the interface pressure between the below knee prosthetic socket and the residual lower limb using pressure sensor. The second type of tests include mechanical test which employed on the specimen manufacturing from the same material of prosthetic socket. This test including tensile test to finding the modules of elasticity (1.109 GPa), yield stress (34 MPa), and ultimate stress (38 MPa).The last part of this work is focus on the simulation of the BK prosthesis, to calculate the equivalent (Von-Mises) stresses, and deflections by using ANSYS software (14.5).The results show that the maximum equivalent Von- Mises stress is equal to (18.5 e7 Pa), also the maximum deflection equal (0.00604 mm).

Keywords: Below Knee Prosthetic, Socket, fatigue, composite materials
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1. INTRODUCTION

The prostheses are generally used to replace missing parts due to illness, injury (trauma) or missing since birth (congenital) ... etc. [1]. Amputation of the limbs (BK or below-knee) amputation, is among the main limb amputation performed most of the time figure (1). The socket is the interface between the patient and the prosthetic, show in figure (2). It is the most important part of the prosthetic. It has to be stable, sturdy, and yet comfortable. If these requirements are not met, the patient will not want to wear the prosthetic, or will be quite unhappy with it [2]. Erin Strait [3] studied the design of socket, leather and wooden sockets used to be very popular, but they need great skill and a long working time. This socket was made by sculpting a piece of wood and was attached using traditional methods with the pylon, the leather /metal limb is also manufacturing from metal bars, a thick piece of leather, and a pylon made from wood. In 2016 Muhammed A. M. [4], studied the mechanical properties for hybrid composite materials, which consist from fiberglass, carbon fiber, perlon, and epoxy resin. The Fatigue and tensile tests are performed on this lamination. Result show that, when increased numbers of perlon layers to 11 stratums, the young modules E are clearly improved 44% but the tensile strength decreased 22%. Muhsin J. J. et. al. (2009) [5] investigated the properties of a materials used in the manufacture of above knee prosthetic socket. Materials used are perlon, fiberglass, and acrylic resin. It has been manufacturing fourteen sockets each one different from the other either at lamination or materials used, and Also Studied increase and decrease the number of layers perlon and fiberglass on the mechanical properties. Results show that the lamination which is made of (2perlon+2fiberglass+2perlon) gives the optimum mechanical properties. A. P. Irawan et al (2012) [6] used epoxy with reinforced fiber (bamboo) to manufacturing composite socket, which is cheap and has good strength. Laminated composites are made of woven bamboo fiber at thickness 0.3 ± 0.05 mm and width 3 ± 0.5 mm with volume fraction (10%, 20%, 30%, 40%, and 50%). Compression, tensile, and impact tests are used. The results show that, the epoxy with reinforced fiber bamboo composite at (40%) volume fraction gives results better than composite at (10%, 20%, 40%, and 50%) (tensile strength is 78.09 ± 1.97 Mpa, modulus of elasticity is 8.96 ± 0.33 Gpa, impact strength is 1.3 KJ/m2, and compressive strength is 87.1 ± 4.3 KN).

The main objectives of this work are, improving and strengthen the prosthetic socket by using composite material (4pyrlon, 2carbon, 4pyrlon). Design and analysis the prosthetic socket to determine the subjected stresses, deformation. Study the patient conformability measuring interface pressure through F- socket instrument.

Figure 1 Amputation below the knee

Figure 2 Prosthetic Socket

2. THEORETICAL AND NUMERICAL ANALYSIS

2.1. Phases of Gait Cycle

There are two stages of the gait cycle, which are:

2.1.1. The Stance Phase

Approximately 60% of the walking cycle is the first contact (Heel strike) to toe off. The stance phase is divided into five sub-phases as shown in figure (3). **[7]**

2.1.2. The Swing Phase

This stage begins at the moment the big finger moves away from the ground and ends with touching the tip of the tip or the direct stitch of the heel. From three sub phases (initial, initial, and terminal) the swing phase is consisting. [7]

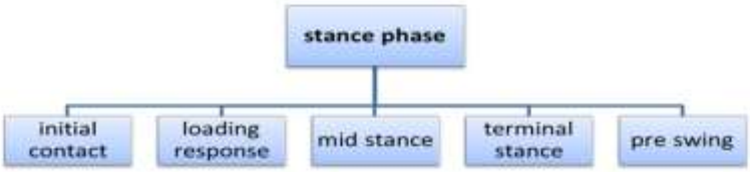


Figure 3 The Five Stages of Stance Phase

2.2. The Ground Reaction Force

During gait and as a consequence of the force placed on the ground when the contact with the foot occurs, the ground reaction forces (GRF) is develops. The ground reaction forces are equal to the force between the foot and the ground. The ground reaction forces are directly related to the acceleration of the COM and can be described simply according to Newton's law by equation

$$GRF = M (g + a) \quad 1$$

Where GRF is the ground reaction force, (g) is acceleration of gravitational, (a) is the center of mass' s (COM) vertical acceleration, and (M) is the person body mass. Since (M) and (g) are constants, the changes in the magnitude of GRF depend only on the changes in the vertical acceleration **[8]**.

3. THE NUMERICAL ANALYSIS

The finite element method was used in this work by software ANSYS (14.5) Workbench as a numerical solution, to determine equivalent stress, and total deformation **[9].** For the 3-D modeling of solid structures, a solid 45 was used. this element (solid 45) consist from eight node with three degrees of freedom. as shown in Figure (4). Figure (5) show the mech of socket.

4. EXPERIMENTAL WORK

4.1. Manufacturing of BK Prosthesi

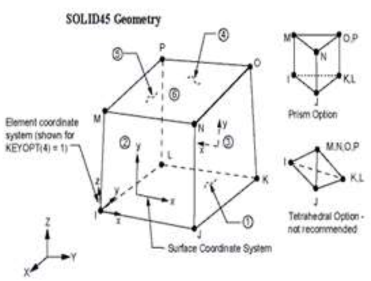
The materials used in this work, for manufacturing lamination of the BK prosthetic socket, are lamination resin 80:20 polyurethane (proter hand icap technology). Fiber carbon stockinet (ottobock health). Hardening powder (ottobock health care 617P37). Polyvinyalcohol PVA bag (ottobock health care 99B71).and Perlon stockinet white (ottobock health care 623T3). as shown in Figure (6). In this work, the Jepson Mold for BK Socket is show in figure (7).

The procedure to Manufacturing socket are:

1. The inner bag (PVA) is pulled into the mold and the pressure valve opens to 35 mm Hg.
2. The fiber carbon stockinet and perlon stockinet are putting (3Perlon and 3fiber carbon and 3perlon) layers and the outer bag is then pulled out and the cotton thread is used to attach the PVC bag to keep the smaller tip on the valve
3. After that, mixing 1.1 liter of resin (polyurethane) with 70 Grams of hardener powder, see figure. (8).
4. The mixture is placed inside the outer bag and the bag is moved to ensure the homogeneous distribution of the mixture inside the area. The vacuum is kept continuously until the composite material becomes cold and then the bags are lifted.as shown in Figure. (9).

4.2. The Interface Pressure Test

The F-Socket sensor was used to measure the pressure between the regions of leg. The amount of pressure produced during the stance phase is obtained by connecting the sensor and measuring its response. Using recording data and computer, the F-Socket sensor is interface with them. The pressure was measured in leg regions. Every position in leg regions was divided longitudinal for three parts. The positions of F-Socket sensor to measured pressures is shows in figure (10). Tables (1) show the case study Data of this work.



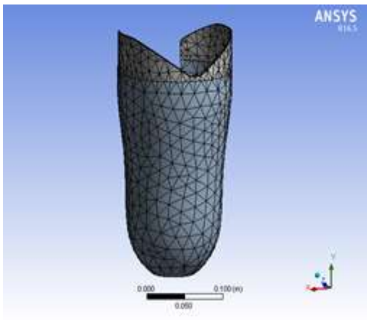


Figure 4 Solid Element Geometry **Figure 5** The model of below knee socket with meshing

Figure 6 Materials Used in BK Socket Lamination

Figure 7 Jepson Mold for BK Socket

Figure 8 Mixing the Hardener with Lamination

Figure 9 Manufacturing of BK Prosthetic Socket

Figure 10 Position of Sensor of Pressure for Man with Below Knee.

Table 1 Case Study Data of this Work

Gender	Age	weight	Length	Type of amputation	Side amputation	The length of amputation
male	23	85	175 cm	BK	Right leg	**19 cm**

The device provides minimum and upper values of pressure and changes those values over time, where the highest value of the pressure is highest obtained **[10]**

4.3. Gait Cycle Test

The main force acting on the human body during walking is the ground reaction force. This force has vertical component **[11]**. During the patient's walk on the plate of forces these vertical forces are generated. Because of the biochemical effects on the leg during stance and gait, the ground reaction force (GRF) is generated. In this test, the "force plate" was used as shown in figure (11).

Figure 11 Ground reaction force test.

In this work a male with an amputation below the knee was treated in his right leg. Using device "force plate" consists of sensors for measuring ground reaction forces and center pressure of the patient. This test was done at Biomedical Engineering Department in AL-Nahrain University

4.4. Tensile Test

The tensile specimen was (4.5 thickness, 11.7 mm width, and 108.7 mm length). The tensile test sample is shows in figure (12). This test was done at University of Nahrain as shown in figure (13). The aim of the test is finding the modules of elasticity, yield stress and ultimate stress which concerned very important parameters can insert in analysis by using ANSYS (workbench). The strain rate of tensile test is 2.000 mm /min. Figure (14) show the sample after tensile test. **[12].**

Figure 12 Shape of Lamination Specimen Before Test **Figure 13** Tensile Test Machine

Figure 14 Tensile Test Specimen After Test

5. RESULT AND DISCUSSION

5.1. Tensile Results

Table (2) show the mechanical properties of composite laminated samples (3 pyerlon,3 fiber carbon,3 pyerlon).

Table 2 Mechanical Properties of Material Socket.

σ_Y **MPa**	σ_{Ult} **MPa**	**E GPa**
25	33	1.3

5.2. Results of Gait Cycle Test

Table (3) gives the step table for male with below knee prosthesis in right leg. his weight is (85kg and the length is 175 cm) and listed in. From table, it can be seen that, the percentage of difference between infected and healthy limb is about 35%. Table (4) gives the gait cycle for the lamination material. The result compares between the healthy (left leg) and infected (right leg). All the gait cycle parameter gives acceptable result.

Table 3 Step Table for Lamination Material

Step Table	Infected Limb	Healthy Limb	Percentage of Difference %
Time of step (sec)	0.91	0.82	-10
Length of step (m)	0.22	0.34	35
Velocity of step (m\sec)	0.45	0.58	22
Width of step (m)	0.14	0.16	12

Table 4 Result of Gait Cycle Test

Gait Cycle Test	Healthy Limb	Infected Limb	Percentage of Difference %
Time of total double (sec)	0.44	0.43	2
Time of Foot Flat (sec)	0.31	0.00	100
Time of stance (sec)	1.25	0.84	32
Time of gait cycle (sec)	1.89	1.26	33
Time of initial double support (sec)	0.09	0.28	210
Time of swing (sec)	0.88	0.79	10
Time of Mid Stance (sec)	0.38	0.46	21
Terminal Double	0.30	0.18	40
Single support time (sec)	0.9	0.56	37

5.3. Result of Interface Pressure Test

Surface pressure values were obtained for four areas (Posterior, Lateral, Medial, and Anterior), These areas were also divided into three parts (lower, middle and upper) areas.

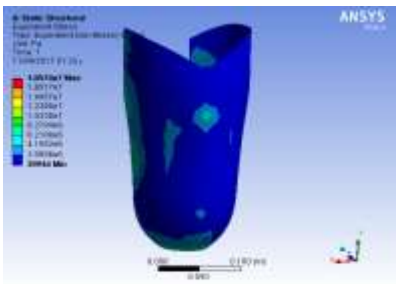
The pressures were measure on these areas in the upper part of posterior region and lower part of anterior region of soft socket. Table (5) shows the interface pressure of leg at four regions Anterior, Lateral, Medial, and Posterior. From tables, the maximum values if interface pressure is occurred at upper posterior regain.

Table 5 The Interface Pressure in Each Region of Leg

Region	Upper Region (KPa)	Medium Region (KPa)	Lower Region (KPa)
Anterior	220	260	175
Medial	175	197	103
Lateral	184	264	201
Posterior	515	189	235

5.4. Results of Numerical Solution

The results show that the maximum equivalent von mises stress equal (1.85 e7 Pa), while the minimum equal to (39946 Pa) as show in figure (15). The deformation analysis gives the total deformation with maximum value equal to (0.006 mm) while the minimum value (0 mm) as show in figure (16)



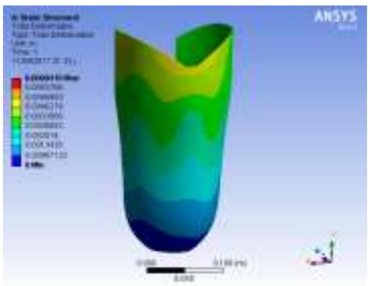


Figure 15 Equivelant Stresses on the Socket **Figure 16** Total Deformation on the Socket

6. CONCLUSION

The main conclusions of this work are:

1. All the gait cycle parameter gives acceptable result during which the maximum difference not exceeded (1%).
2. The maximum equivalent von mises stress equal (1.85 e7 Pa), while the minimum equal to (39946 Pa).
3. The maximum interface pressure is occurred at upper posterior regain.
4. The deformation analysis gives the total deformation with maximum value equal to (0.006 mm) while the minimum value (0 mm)

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