Dynamic Stresses and Deformations Investigation of the Below Knee Prosthesis using CT-Scan Modeling

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Abstract— The main issue of this research to improve and develop the mechanical properties of the socket composite material for below-knee (BK) prosthesis; and study the stresses and deformations that are developed due to the dynamic loading caused in the gait cycle. The suggested composite material was consisting of the following layers (2perlon +1kevlar +1perlon +1kevlar +2perlon) as 7 layers and 3.5 mm thickness. This research involved two main parts experimental and numerical. The experimental parts investigation the ultimate tensile strength and modulus of elasticity, (187 MPa) and (1.78 GPa) respectively for the suggested material. The experimental part also included the measurement of the ground reaction force test (GRF). The results showed that the suggested socket was close to symmetrical by (96%) as comparing with the intact leg. The numerical part depends on ANSYS 16.0 to calculate the dynamic stresses and deformation. Modeling of the socket was developed by using CT—Scan method and exported to ANSYS 16.0. The dynamic results showed that the maximum stresses (107 MPa) and the total deformation was (18 mm) for the suggestion socket when assuming the applying load as unit step. The dynamic load factor (DLF) was (1.18).

Index Term— Kevlar, Below Knee Prosthesis Dynamic Stress, CT Scan.

I. INTRODUCTION

The modified for mechanical properties and behavior for below knee prosthesis and socket part investigated from many researchers at previous years. Therefore, more study gold to increase strength for materials used for manufacturing the socket. Then, can be using various way to modified the mechanical properties and behavior for its parts, as, change the reinforcement fiber types, change the reinforcement fiber volume fraction, change the laminated sconces … etc. Therefore, same researchers listing below shown same ways to modified the strength and properties for materials used, as, Firstly, M. J. Jweeg et. al, [1-3], from 2011 to 2017, investigated the effect for materials properties changing on the various mechanical properties and stress behavior for foot, socket, and prosthetic below knee, in addition to, investigated the creep and fatigue characterizations for materials used to manufacture its parts, by using experimental and theoretical techniques. After this, J. S. Chiad et. al, [4-5], at 2012 and 2018, investigated the vibration analysis for below knee and stress distribution by using experimental techniques. The, A. M. Takhakh et. al, [6-8], at 2013 and 2018, studied the vibration and other mechanical properties and behavior for various Orthosis part with various materials type parameters. After this, J. K. Oleiwi, [9-10], at 2016 and 2018, investigation the effect of materials properties with various reinforcement effect on the stress analysis for various foot and, prosthetic and biomechanical applications parts. Then, M. A. Al-Shammari, [11-12], at 2017 and 2018, presented the stress and fatigue analysis for knee prosthesis sockets with various reinforcement materials effect experimentally. Also, at 2017, K. K. Resan, [13], investigated the effect of ultraviolet radiation on the fatigue behavior of below-knee sockets, with and with-out Heat effect, by using experimental technique. Finally, M. Al-Wailly, [14-17], at 2018, investigated for the reinforcement fiber type effect on the various mechanical behavior for foot and below knee, as stress and fatigue behavior for materials used, in addition to, investigated the temperature effect on the fatigue behavior for foot part. Also, the investigation included analysis for Biomechanical and gait assessment for normal and Legs.

Therefore, in this work the ultimate tensile strength, the modulus of elasticity and dynamic load factor for the suggested marital will be determining. The material properties will be inserted to the ANSYS 16.0. While the modelling of the socket will be made by using CT-scan method.

When, the application of CT-Scan modeling has been used by a few researches before, because of its difficulty. Diane Higgs and Phavan Sanders [18] developed a design for below knee prosthetic. The design was based on prescribed specification, which includes manufacturing process, material, physical active data points were acquired from a CT scan of a residual limb and allowance was made in pressure areas. Figure 1 shows the CT-scan slices for the tibia crest. The socket model was imported into ANSYS 5.7 for finite element analysis.

Fig. 1. Modified Slice of the Tibia Crest [18]
Sam L. Phillips et al [19] have made eight varieties of lay-up materials (fibers) each laminated separately with one of three common resins (matrix), resulting in 24 combinations of fiber/resin laminates. The weakest were laminates with fibers of perlon or Nyglass stockinette, spectralon, nylon, and cotton, ranging between 18 and 42 (MPa); the middle was fiberglass, ranging between 67 and 109 MPa; the highest strengths were found in carbon fiber laminates, ranging between 236 and 249 MPa. As shown in figure 2 (A and B) and figure 3 (A and B).

II. EXPERIMENTAL PART

The experimental technique included manufacturing and testing for the below knee structure with materials combined. Where, the testing samples are manufacturing accordant to ASTM stander, [20-29], with various composite combined reinforcement effect.

The experimental part consists of manufacturing the below knee prosthetics by using the following material and equipment, knit from perlon, kevlar fibers, laminations resin 80:20 polyurethane, and, hardening powder.

II.1. Equipment of Manufacturing the Prosthetic Socket

Gypsum mold: Mold is made of gypsum material with an external shape of parallelogram with dimensions of 12 cm 12 cm 30 cm. This mold underwent operations sculpt and refine of the surface because the inner surface of the material to be manufactured will take the form of the outer surface of the mold see figure (4a). Vacuum system: It includes pipes and vacuum pump. It is used for suction the air completely from two possible gaps between the PVA and the gypsum mold and between the inner and outer plies of PVA. There are several benefits of vacuum system. In the first gap vacuuming gives a perfect shape for gypsum mold and prevents creating bubbles between the mold and PVA. For the second gap vacuum is used to remove the air between the PVA and the part of casting process. Moreover, vacuum process insures no bubbles created during the casting process and insure the suitable distribution of the risen throw all the layers figure (4b).
II.2 Procedure of Manufacturing Prosthetic Socket

The following steps were followed:
1. Putting the first piece from the PVA on the gypsum molds as shown in figure (2a) and suction the air between PVA and gypsum by the vacuum system.
2. Putting the first Knit of perlon as shown in figure (2b) that density is 0.01331g/cm².
3. For available material Putting the mat from Kevlar fiber with density is 1.44 g/cm².
4. Putting the second Knit of perlon that density is 0.01331 g/cm² and the second piece of PVA and suction the air between two bags by the vacuum system. Mix the laminations resin with hardening powder put this mixture on these layers as distributed equally as shown in figure (5d).

II.3. Tensile Test

yield stress and ultimate stress for each material used for suggested prosthetic socket. Standard tensile test specimens were cut from the final product according to the American Society for Testing and Materials (ASTM) D638 [30-38]. Three specimens were cut for each lamination, [39-42], at the workshop using a computer numeric control (CNC) machine as shown in figure 6 and figure 7.

II.4. Free Vibration Test

The test can be Concisely into the following:
1. The testing device consists of a special testing hammer, accelerometer, amplifier and monitor as shown in Figure 8.
2. The manufactured socket was fixed from the adaptor as a boundary condition.
3. The position of the nodes to be tested are marked as shown in figure 9.
4. The testing hammer used to produce the natural frequency by hitting the fixed socket a quick and strong hit; this operation has been done fourth times for the same node but the hit was in deferent direction.
5. Finally, the frequency waves were recorded and saved in USB flash memory.

III. NUMERICAL ANALYSIS FOR BELOW KNEE PROSTHETIC SOCKET

The finite element method (FEM) is extensively used in the multi purposes fields in engineering and science, [43-51], taking the advantage of the rapid development of digital computers with large memory capacity, by fast computation. The method is recognized as one of the most powerful numerical methods because of its capabilities which include complex geometrical boundaries and non-linear material properties. In this work, FEM with the aid of ANSYS workbench 16.0 software is used as a numerical tool to illustrate the effect of the fatigue performance in a structure element to determine the behavior of stress distributions contour, total deformations, and areas of safety factor. The general analysis by using ANSYS workbench version 16.0 has three distinct steps they are, [52-58]:
1. Building the geometry as a model.
2. Applying the conditions of boundaries load and get the solutions.
3. Reviewing the results.
III.1. CT-Scan of the Below Knee Prosthesis
A below-knee amputee socket has been modeled by using CT-scan method in AL-Kafeel hospital/kerbala/iraq, the obtaining slice pictures from CT-Scan for the designed socket had been exported to (Materialise Mimics Innovation Suite 17.0) where the 3D modeling which created as shown in Figure 10. The generated geometry was not uniform because of the stainless steel adapter joint makes the X-Ray shuttering. As shown in figure 11.

![CT-scan generated geometry](image1)

![The Shuttered Area Around the Socket Adapter](image2)

After making a lot of editing steps included erasing and redrawing soothing and wrapping which makes the geometry acceptable and ready to be analyzing, as in Fig. 12.

![The Final Shape of Socket. after editing.](image3)

III.2. Mesh of the Model
The meshing process has been done by choosing the volume, and then the shape of element was selected as tetrahedron (Automatic meshing), [59-70], for The prosthetic socket as shown in figure 13. This meshing contains on 350000 elements according to, triangular method has been chosen ANSYS elements and nodes counter.

![The model of BK socket with meshing](image4)

IV. RESULT AND DISCUSSION
IV.1. Experimental Results
A. Mechanical Properties
The mechanical properties as (σult and E) of each tested spaceman material represent the average value for three attempts are listed in Table. I. These properties will be used later in the program ANSYS 16.0 to simulate the prosthetic socket and analyze stress and deformation.

<table>
<thead>
<tr>
<th>Material</th>
<th>suggested</th>
<th>available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate stress σ ult (MPa)</td>
<td>177.9</td>
<td>33.65</td>
</tr>
<tr>
<td>Modulus of elasticity (E) (GPa)</td>
<td>1.87</td>
<td>0.941</td>
</tr>
</tbody>
</table>

B. Natural Frequency Results
Natural frequency results were achieved at university of kuffa/department of mechanical engineering, by testing ten different positions and take the average results for each suggested node it was about (69.3) as shown in figure (114) while the other ten nodes result have listed in table II.

![Natural frequency wave for the second nod](image5)
Table II
Ten Nods result for the socket

<table>
<thead>
<tr>
<th>Nodes No.</th>
<th>Natural Frequency (HZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.665</td>
</tr>
<tr>
<td>2</td>
<td>69.275</td>
</tr>
<tr>
<td>3</td>
<td>69.58</td>
</tr>
<tr>
<td>4</td>
<td>67.749</td>
</tr>
<tr>
<td>5</td>
<td>70.496</td>
</tr>
<tr>
<td>6</td>
<td>70.496</td>
</tr>
<tr>
<td>7</td>
<td>69.58</td>
</tr>
<tr>
<td>8</td>
<td>69.29</td>
</tr>
<tr>
<td>9</td>
<td>68.359</td>
</tr>
<tr>
<td>10</td>
<td>69.27</td>
</tr>
</tbody>
</table>

Average 69.276

C. Gait Cycle Results
The results of a step for the two cases (available and suggested socket) are summarized in Tables III and Table IV respectively. The results include the prosthetic left leg (injured leg) and right leg (intact leg) for two cases. For the step-strip specification result the differences can be observed between the injury leg and normal leg for the two cases (suggested and available socket). The difference in the step length for the suggested socket was (0 cm) while it was (6 cm) for the available socket; this gives enhancement by (100 %). For the step time difference, it was (0.02 sec) for the suggested socket while it was (0.05 sec) for the available socket so it was enhanced by (60%). Also the foot rotation angle difference for first case was (0.9 deg), while its being (4.2 deg) for the second case and thus it’s have been enhanced (78.5%).

The result that obtained in figure 15 and figure 16, have shown that the difference in gait cycle length and single support line was (10mm) and (4mm) respectively; for the suggestion socket. While for the polypropylene socket it was (37mm) and (47mm) respectively.

Table III
Step-Strip and gait cycle results for suggestion prostheses socket.

IV.2. The Numerical Results
The static, dynamic and natural frequency properties of prosthetic socket were investigated using finite element method. The suggested prosthetic socket (2perlon +1kevlar + 1perlon+ 1kevlar +2perlon) was analyzed statically and dynamically; by simulations conducted by using (ANSYS 16.0) workbench software for the analytical part.
A. Static Results
The equivalent Von-Mises Stresses analysis gives a knowledge on the amounts of stress and deformation generated by the interface pressure in the socket. The highest stress value was 107 MPa in the socket made from the suggested material as shown in figure (17) while the total deformation was not exceeding 21 mm in some thin area as shown in figure (18).

![Fig. 17: Von-Mises stress of suggested prosthetic socket material](image1)

B. Dynamic Results
The dynamic analyses is the actual state for the all movement application so to make that available for the prosthetics socket it has been assumed to cases the first was subjected the socket to unit step force its value was 700 N as shown in figure 19 (from the GRF test). The obtained results for the first case showed that the maximum stress was 107 Mpa as shown in figure (20). While the total deformation was 24 mm as shown in figure (21). Also figure (22) and figure (23) showing the stress and deformation verses time curves during one second.

![Fig. 18: Total deformation for suggested prosthetic socket material](image2)

![Fig. 19: Unit Step force during 1 second for both sockets.](image3)

![Fig. 20: The equivalent stress at the last second for the unit step force.](image4)

![Fig. 21: The total deformation in the last second for the unit step force.](image5)

![Fig. 22: Dynamic stresses during 1 second for the unit step force.](image6)

![Fig. 23: Total deformations during 1 second for the unit step force.](image7)
While in the second case it was assumed that force is sinusoidal as shown in figure (24). The second case showed that the maximum developed stress and deformation was 147 MPa and 22 mm respectively at 0.8 second as shown in figure (25) and figure (26). While the stress-time and deformation-time curves have shown in figure (27) and figure (28) respectively. The dynamic load factor has been calculated by dividing the dynamic stress on static stress.

$$DLF = \frac{\text{dynamic stress (MPa)}}{\text{static stress (MPa)}}$$

It is found that DLF does not exceed (1.188) for the suggested socket material.

Fig. 24: Sinusoidal force during 1 second.

Fig. 25: The maximum stress value at 0.8 second.

Fig. 26: The deformation value at 0.8 second.

Fig. 27: Stress-time curve for the sinusoidal force.

Fig. 28: Deformation-time curve for the sinusoidal force.

V. CONCLUSIONS
The following points are concluded as follows,
1. To have a uniform solidification the ambient temperature should be more than 240 C for the lamination risen 80:20.
2. The mechanical proprieties for the suggestion material (2 perlon +1 kevlar +1 perlon +1 kevlar +2 perlon) show better results than available material (polypropylene). Where the ultimate tensile strength and modulus of elasticity are increased by (428.6%) and (98.7%) respectively.
3. CT-scan method was very powerful in FEL modeling geometry compared to the normal geometry representation of the socket.
4. From the gait cycle results, it was observed that the suggested socket prostheses decrease the butterfly parameters, the difference between the injury leg and the intact leg. the butterfly parameters and the gait cycle step time enhanced by (60%).

REFERENCES
[4] Bashar A. Bedaiwi and Jumaa S. Chiad ‘Vibration analysis and measurement in the below knee prosthetic limb part I: Experimental


