A Finite Element Simulation of Nano Effects on Stress Distribution in a Below Knee Prosthetic

Muhsin J. Jweeg¹, H. A. Hamzah², Muhannad Al-Waily³*, Mohsin Abdullah Al-Shammari⁴

¹Al-Farahidi University, College of Technical Engineering, Iraq
²University of Kerbala, College of Engineering, Prosthetics and Orthotics Engineering Department, Iraq
³Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Iraq
⁴University of Baghdad, College of Engineering, Department of Mechanical Engineering, Iraq

* muhanedl.alwaeli@uokufa.edu.iq

Abstract. In the authors’ previous work, various mechanical properties such as modulus of elasticity, strength, creep, impact and fatigue behaviours for different laminates composites with and without different Nano-material additions and reinforcements with different types of fibres were tested experimentally. The four best lamination types and suitable Nano-material percentages were used in this work to develop a numerical investigation of a below knee prosthesis, facilitating the investigation of the effect of different Nano-material types and weight fractions on the stress and deformation in below-knee socket prosthetic structures manufactured from composite laminated materials with various reinforcement fibres. Numerical analysis using the finite element method was adopted to estimate the Von Mises stresses and deformation behaviours for the below-knee prosthetic structures, with the mechanical properties of the relevant composite materials taken from previous published work. The comparison of different Nano-material types and weight fractions suggested that the best Nano-material was SiO2 at a weight fraction of about 2% for the sample 2Perlon+2Kevlar+1Perlon+2Carbon+1Perlon+2Kevlar+2Perlon, where the stress for the socket was reduced by about 40%, with a reduction in the deformation of about 38%.

Keywords: Laminated Composite, Prosthetic, Below Knee, Composite, Numerical Technique.
Introduction
An increasing number of amputees is emerging in developing countries for several reasons, including landmines in countries suffered from war, diseases, traffic accidents, and congenital deformities in which a child is born with damaged or missing limbs. These issues have driven research activity in terms of developing new materials for socket manufacturing for prostheses. In Iraq, many researchers have worked on developing new materials [1-10] and proving their effectiveness from the perspective of the requisite strength and stiffness to weight ratios, with the resulting materials finding wide application in rehabilitation centres in Iraq. The application of composite materials in particular has allowed the construction of many improved engineering structures, such as the sockets manufactured in rehabilitation centres [11-18].

There is a high demand on prostheses in terms of durability, and they must also be easy to use, cheap, reliable, and able to sustain both static and dynamic loading as well as offering good damping characteristics in different gait cycles [19-26]. Bedaiwi et al. [1] experimentally investigated the dynamic behaviours of below knee limb prostheses based on the calculation of the vibration characteristics for below knee limb structures. Jweeg et al. [3] studied the optimum design for prosthetic sockets by designing and manufacturing prosthetic sockets then estimating the stress behaviours for the socket structures numerically to calculate the stress distributions on the sockets. Jweeg et al. [4] also analysed the behaviours of a prosthetic foot under temperature effects, including the calculation of stresses and deformation in the prosthetic foot. That study included experimental research, to determine the mechanical properties of the materials used in manufacturing the foot structure, and numerical calculation using the finite element method, to calculate the stress distribution and deformation behaviours of the foot under different temperature effects. Takhakh et al. [5] experimentally studied the mechanical properties and gait cycle parameters of a below knee socket before using numerical analysis using the finite element method to evaluate the different mechanical behaviours of the socket throughout the gait cycle.

Jweeg et al. [6] used CT scans to investigate the stress distribution and deformation in a below knee socket under dynamic behaviour effects. The study included experimental and numerical work in order to investigate the stress and deformation and to compare the obtained results with theoretical expectations. The experimental work included the manufacturing of socket parts and estimation of the mechanical properties of the materials used, with the stress and deformation investigated using a CT scan technique. The numerical work, using the finite element method, was then used to evaluate the stress and deformation under dynamic loads. Abbas et al. [17] studied the fatigue behaviours of different composite materials used to manufacture prosthetic sockets. Different composite specimens with various lamination sequences were manufactured and tested to estimate their mechanical properties and to evaluate their fatigue strength and life. Numerical analysis was also utilised to evaluate the fatigue life and strength for the materials, and the numerical results were compared with the experimental results. Al-Waily et al. [18] improved the fatigue strength and life of various composite materials used to manufacture prosthetic sockets by adding different Nano-material types and volume fractions. Their investigation was conducted experimentally and numerically in order to evaluate the fatigue behaviours for different materials. Different tensile and fatigue samples for composite materials were manufactured and tested to estimate their mechanical properties and fatigue characterisations. The numerical technique was used to evaluate the fatigue behaviours for different composite material types in comparison with the obtained results, and reasonable agreement was found between the experimental and numerical results.

It can be seen from the results of such previous work that the addition of different Nano-materials leads to varying improvements in the mechanical properties and fatigue behaviours of composite materials, with improvement percentages of approximately 30%. In this work, the materials examined in previous work by the authors [18] are simulated using the finite element technique in order to predict their efficiency in terms of manufacturing prostheses and assessing their stress levels in order to develop recommendations for manufacturers with regard to the application and effectiveness of using Nano particles within the composites selected for prostheses.
Theoretical Investigation

1.1. **Analytical Modelling**

An ordinary model was formed to evaluate the forces between the limb and the prosthetic socket [19-26]. To replicate the actual forces between the prostheses and the stump, a conical shape was generated due to the forcing of the socket shell. The inner bone is assumed to be a cylinder, \( F = Kd \), and the material is assumed to be linear and isotropic. The analysis also assumes full contact between the prostheses and the stump. As shown in Fig. 1, two forces affect the tissue. The first force is the perpendicular spring presupposed in the sample as the supporting force generated by compressing the soft tissue normal to the surface of residual limb. The second force is the tangential spring representing the force from the parallel shear to the interface. The average interface normal and shear stresses were evaluated based on equation (1) [19].

\[
P = \frac{K_N}{A} \left( d_{N_o} + \frac{W \sin \theta}{(K_N \theta + K_S \cos^2 \theta)} \right),
\tau = \frac{K_S}{A} \left( -\frac{K_N}{K_S} d_{N_o} \tan \tan \theta + \frac{W \cos \theta}{(K_N \theta + K_S \cos^2 \theta)} \right)
\]

Where, 
- \( P \): The average interface normal stress in (Pa), 
- \( \tau \): The average interface shear stress in (Pa), 
- \( d_{N_o} \): Pre-compression of the perpendicular spring, 
- \( K_N \): The constants of the perpendicular spring (N/mm), 
- \( K_S \): The constants of the tangential spring (N/mm), 
- \( W \): The bone force (N), 
- \( A \): Surrounding socket area (mm\(^2\)), 
- \( \theta \): the conical angle (degree).

MATLAB R2008a software was used to create a program using analysis model equations. The normal and shearing stresses were then evaluated based on equation (1).

![Figure 1. The simplified remaining limb model.](image)

1.2. **Finite Element Technique**

Many engineering problems are now solved efficiently using software packages [27-33] such as SOLIDWORKS and ANSYS, which utilise the finite element analysis technique as an effective tool to determining solutions to difficult problems. Finite element analysis (FEA) is a computerised method for solving problems in areas such as vibration, heat, fluid flow, and other physical effects. The results can be used to indicate if a product may break or wear out, or even if it will work in the way it was designed. SOLIDWORKS software is one of the most common finite element software programs, and in this work, a SOLIDWORKS program was used to generate an analysis BK socket, as this allowed the type of material used to be changed. The model of the below-knee socket was plotted in SOLIDWORKS software (version 2015) by entering the real dimensions to determine the real shape of the socket.

SOLIDWORKS analysis works by dividing the generated object into a huge number of elements [34-39]. Built-in mathematical equations are then used to estimate the behaviours of each element. A shell element is defined by three corner nodes, three mid-side nodes, and parabolic edges that connect all these nodes together. Each node in a shell element has six degrees of freedom, three translations and three rotations. Figure 2 shows the socket model and figure 3 shows the geometry and node locations for this element. The advantages of using a parabolic element include the fact that the represented curve
boundaries are more accurate, thus producing better mathematical approximations. After selecting the type of element, the desired thickness was inserted [40-45], and the material used in each case selected from the materials library or otherwise input. In this case, the types of composite materials used required the mechanical properties such as yield strength and Young’s modulus to be inserted into the library, as shown in Table 1 [18]. The boundary conditions assumed that the socket was fixed at the bottom, with the accessories of the foot and the amputee position joined mechanically with the socket. In the upper section, the weight loading was applied where the socket fits on to the stump. The internal pressure between the stump and the socket was thus calculated according to the relevant interface pressure equations, solved by MATLAB.

![Figure 2. Socket Modelling.](image)

![Figure 3. Shell Element](image)

**Table 1. Mechanical Properties for Composite Laminated Prosthetic, [18].**

| Sample | Lamination Scheme | Perlon | Fibre | Resin | E (GPa) | $\sigma_{ult}$ (MPa) |
|--------|-------------------|--------|-------|-------|---------|----------------------|
| $S_1$  | 3Perlon+2Kevlar+2Perlon+2Glass+3Perlon |        |       |       | 31.5    | 118.3                |
| $S_2$  | 3Perlon+2Carbon+2Perlon+2Glass+3Perlon |        |       |       | 24.6    | 95.3                 |
| $S_3$  | 3Perlon+2Kevlar+2Perlon+2Carbon+3Perlon | 28 %   | 18 %  | 54 %  | 26.3    | 102.3                |
| $S_4$  | 2Perlon+2Kevlar+1Perlon+2Carbon+1Perlon+2Kevlar+2Perlon |       |       |       | 36.8    | 128.36               |

**Results and Discussion**

The results for stress and distribution were obtained for specimens as shown in Table 1, with the addition of nanoparticles; the mechanical properties were as shown in Table 2. Tables 3 and 4 show the stress and deformation in the socket, while Figure 4 shows the Von Mises stress distribution for the socket model using Al$_2$O$_3$ and SiO$_2$ with nanoparticles as in specimen $S_1$ in Table 1. Figure 5 shows the contours of the Von Mises stress for the socket with Al$_2$O$_3$ and SiO$_2$ Nano-material as in sample $S_2$. It was found that the addition of Nano-materials reduced the stresses induced in the socket; the maximum reduction was found for 2% inclusion, with a reduction percentage of 23% on using Nano SiO$_2$ and 20% on using Nano Al$_2$O$_3$.

The basic conclusion is that sockets may be manufactured with the addition of Nano-materials to facilitate a reduction in weight and cost; this is therefore recommended for rehabilitation centres attention. Tables 3 and 4 also suggest that the Von Mises stresses and deformation decrease with the increase in Nano-material volume fraction, with improvements of about 21% on using of SiO$_3$ Nano-materials and 24% on using Al2O3 Nano-materials. The socket weight ended up at about 0.7 kg, yet the stiffness to weight ratio was increased by Nano-material reinforcement. Other composite material samples $S_2$, $S_3$, and $S_4$, as shown in Tables 3 and 4 also demonstrated change to Von Mises stresses in addition to stress and stiffness to weight ratios under different Nano-material effects. From Tables 3 and 4 and figures 4 to 7, it can thus be concluded that the stress in composite samples is reduced with the
increase in Nano-material volume fraction values, while the stiffness for composite materials is increased by increasing the Nano-materials weight fraction values.

1. Stress was reduced by 20% and an increase in the stiffness to weight of up to 35% was seen with reinforcement using SiO2 Nano-materials. Stress was reduced by 9%, and an increase in stiffness to weight ratio of 35% was seen with Al2O3 reinforcement in sample S2.

2. Stress was reduced by 18% and an increasing of the stiffness to weight ratio of up to 34.5% was seen with reinforcement using SiO2 Nano-materials. Stress was reduced by 12.5% and an increase in stiffness to weight ratio of about 29% was seen with Al2O3 reinforcement in sample S3.

3. Stress was reduced by 40% and an increase in the stiffness to weight of up to 35% was seen with reinforcement using SiO2 Nano-materials. Stress was reduced by 30%. An increase in the stiffness to weight ratio of about 38% was seen with Al2O3 reinforcement in sample S4.

Figure 8 shows the deformation contours for the socket model using Al2O3 and SiO2 Nano-materials in sample S1. The maximum deflection was reduced from 0.131 to 0.074 mm on using SiO2 at 1.5% and from 0.131 to 0.072 mm on using Al2O3 at 2%. The conclusion is that using moderate percentages of Nano-materials within composite materials is a useful means of increasing the weight/strength and stiffness/weight ratios. The overall picture of stress distribution and the deformation form also offers an indication that using the types of laminates (3perlon+2kevlar+2perlon+2Glass+3perlon) with the properties shown in Table 1 allows successful modification using Nano-materials, as indicated in the contours of Figures 4 and 8. In addition, the deformation of the other composite samples, shown in Table 1, was also improved by reinforcement with Nano-materials, as shown in Tables 3 and 4. The deformations of samples S2, S3, and S4 were reduced with increases in the volume fractions of Nano-materials, as shown in figures 9 to 11, with different Nano types having varying levels of effect. The reduction of composite materials’ socket deformation was about 35% for sample S2 with reinforcement with SiO2 Nano-materials, and by 34% with reinforcement with Al2O3 Nano-materials. For sample S3 the reduction of deformation in the composite socket was about 34.5% with SiO2 Nano-materials and 29% with Al2O3 Nano-materials. Finally, for sample S4, the deformation of the socket was reduced by 38.5% and 37.5% by reinforcement with SiO2 Nano-materials and Al2O3 Nano-materials, respectively. Tables 3 and 4 and figures 4 to 11 thus allow the conclusion that the maximum reduction of stress and deformation from shock and maximum increase in stiffness to weight ratios occurred in sample S4. This implies that the best sample for manufacturing a socket structure incorporating Nano-materials is sample S4, with SiO2 Nano reinforcement.

### Table 2. Mechanical Properties for Laminated Composites with Various Nanoparticles.

| Sample | Nano Volume Fraction (%) | Nano Material Type | Nano SiO2 | E (GPa) | σ ult (MPa) | Nano Al2O3 | E (GPa) | σ ult (MPa) |
|--------|--------------------------|--------------------|-----------|---------|-------------|------------|---------|-------------|
| S1     | 0                        | 31.5               | 118.3     | 31.5    | 118.3       |            |         |             |
|        | 0.5                      | 33.2               | 128.9     | 32.6    | 126.9       |            |         |             |
|        | 1                        | 36.8               | 135.4     | 35.1    | 133.7       |            |         |             |
|        | 1.5                      | 39.2               | 146.3     | 37.8    | 145.1       |            |         |             |
|        | 2                        | 42.3               | 158.6     | 41.2    | 156.8       |            |         |             |
|        | 0                        | 24.6               | 95.3      | 24.6    | 95.3        |            |         |             |
| S2     | 0.5                      | 26.4               | 104.5     | 25.3    | 102.8       |            |         |             |
|        | 1                        | 29.7               | 111.7     | 27.9    | 110.2       |            |         |             |
|        | 1.5                      | 33.4               | 120.4     | 31.7    | 118.7       |            |         |             |
|        | 2                        | 36.2               | 130.7     | 35.4    | 128.6       |            |         |             |
|        | 0                        | 26.3               | 102.3     | 26.3    | 102.3       |            |         |             |
|        | 0.5                      | 28.3               | 107.8     | 26.8    | 105.4       |            |         |             |
|        | 1                        | 31.2               | 114.6     | 29.7    | 112.7       |            |         |             |
|        | 1.5                      | 35.8               | 125.4     | 34.3    | 123.6       |            |         |             |
|        | 2                        | 38.7               | 136.7     | 37.1    | 134.4       |            |         |             |
Table 3. Deformation and Stress for Composites with SiO$_2$ Nano-materials

| Sample | Nano Volume Fraction (%) | Maximum Von Mises Stress (MPa) | Maximum Displacement (mm) | Von Mises Weight (MPa/kg) | Stiffness $K$ (N/mm) | Stiffness Weight Ratio (N/mm.kg) |
|--------|--------------------------|-------------------------------|--------------------------|--------------------------|---------------------|---------------------------------|
| $S_1$  | 0                        | 9.2                           | 0.093                    | 13.14                    | 967.742             | 1382.49                         |
|        | 0.5                      | 8.795                         | 0.093                    | 12.56                    | 967.742             | 1382.49                         |
|        | 1                        | 8.199                         | 0.082                    | 11.71                    | 1097.56             | 1567.94                         |
|        | 1.5                      | 7.692                         | 0.074                    | 10.99                    | 1216.22             | 1737.46                         |
|        | 2                        | 7.536                         | 0.074                    | 10.77                    | 1216.22             | 1737.46                         |
|        | 0                        | 10.010                        | 0.131                    | 14.30                    | 687.023             | 981.46                          |
| $S_2$  | 0.5                      | 9.611                         | 0.119                    | 13.73                    | 756.303             | 1080.43                         |
|        | 1                        | 9.642                         | 0.106                    | 13.77                    | 849.057             | 1212.94                         |
|        | 1.5                      | 9.260                         | 0.094                    | 13.23                    | 957.447             | 1367.78                         |
|        | 2                        | 8.100                         | 0.085                    | 11.57                    | 1058.82             | 1512.60                         |
|        | 0                        | 9.624                         | 0.119                    | 13.75                    | 756.303             | 1080.43                         |
| $S_3$  | 0.5                      | 9.121                         | 0.111                    | 13.03                    | 810.811             | 1158.30                         |
|        | 1                        | 8.961                         | 0.082                    | 12.80                    | 1097.56             | 1567.94                         |
|        | 1.5                      | 8.721                         | 0.084                    | 12.46                    | 1071.43             | 1530.61                         |
|        | 2                        | 7.900                         | 0.078                    | 11.29                    | 1153.85             | 1648.36                         |
|        | 0                        | 8.651                         | 0.083                    | 12.36                    | 1084.34             | 1549.06                         |
| $S_4$  | 0.5                      | 7.934                         | 0.077                    | 11.33                    | 1168.83             | 1669.76                         |
|        | 1                        | 7.381                         | 0.071                    | 10.54                    | 1267.61             | 1810.87                         |
|        | 1.5                      | 6.526                         | 0.061                    | 9.32                     | 1475.41             | 2107.73                         |
|        | 2                        | 5.251                         | 0.051                    | 7.50                     | 1764.71             | 2521.01                         |

Table 4. Deformation and Stress for Composite with Al$_2$O$_3$ Nano-materials

| Sample | Nano Volume Fraction (%) | Maximum Von Mises Stress (MPa) | Maximum Displacement (mm) | Von Mises Weight (MPa/kg) | Stiffness $K$ (N/mm) | Stiffness Weight Ratio (N/mm.kg) |
|--------|--------------------------|-------------------------------|--------------------------|--------------------------|---------------------|---------------------------------|
| $S_1$  | 0                        | 9.2                           | 0.093                    | 13.14                    | 967.742             | 1382.49                         |
|        | 0.5                      | 8.961                         | 0.082                    | 12.80                    | 1097.56             | 1567.94                         |
|        | 1                        | 8.635                         | 0.086                    | 12.34                    | 1046.51             | 1495.01                         |
|        | 1.5                      | 8.254                         | 0.082                    | 11.79                    | 1097.56             | 1567.94                         |
|        | 2                        | 8.070                         | 0.072                    | 11.53                    | 1250               | 1785.71                         |
|        | 0                        | 10.010                        | 0.131                    | 14.30                    | 687.023             | 981.46                          |
| $S_2$  | 0.5                      | 9.757                         | 0.124                    | 13.94                    | 725.806             | 1036.87                         |
|        | 1                        | 9.591                         | 0.113                    | 13.70                    | 796.46              | 1137.80                         |
|       | S3       | S4       |
|-------|----------|----------|
| 1.5   | 9.376    | 13.39    |
|       | 0.086    | 1046.51  |
|       | 0.086    | 1495.01  |
| 0     | 9.624    | 13.75    |
|       | 0.119    | 756.303  |
|       | 0.117    | 1080.43  |
| 0.5   | 9.564    | 13.66    |
|       | 0.117    | 769.231  |
|       | 0.086    | 1098.90  |

**S3**

|       | 1       | 2       |
|-------|---------|---------|
| 9.502 | 13.57   | 849.057 |
| 0.106 | 1212.94 |
| 9.223 | 13.18   | 978.261 |
| 0.092 | 1397.52 |
| 8.405 | 12.01   | 1058.82 |
| 0.085 | 1512.60 |
| 8.651 | 12.36   | 1084.34 |
| 0.083 | 1549.06 |
| 8.186 | 11.69   | 1084.34 |
| 0.083 | 1549.06 |

**S4**

| 1.5   | 7.763    | 11.09    |
|       | 0.071    | 1267.61  |
|       | 0.052    | 1406.25  |
| 2     | 6.137    | 8.77     |
|       | 0.052    | 1730.77  |
|       | 2472.53  |

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**a. 0.5% Al₂O₃ Nano**

**b. 0.5% SiO₂ Nano**

**c. 1% Al₂O₃ Nano**

**d. 1% SiO₂ Nano**

**e. 1.5% Al₂O₃ Nano**

**f. 1.5% SiO₂ Nano**
Figure 4. Von Mises (MPa) for Sockets with Al$_2$O$_3$ and SiO$_2$ Nano-materials for sample $S_1$.

- g. 2% Al$_2$O$_3$ Nano
- h. 2% SiO$_2$ Nano
- a. 0.5% Al$_2$O$_3$ Nano
- b. 0.5% SiO$_2$ Nano
- c. 1% Al$_2$O$_3$ Nano
- d. 1% SiO$_2$ Nano
**Figure 5.** Von Mises (MPa) for Sockets with Al$_2$O$_3$ and SiO$_2$ Nano-materials for sample $S_2$. 

- (a) 0.5% Al$_2$O$_3$ Nano
- (b) 0.5% SiO$_2$ Nano
- (c) 1.5% Al$_2$O$_3$ Nano
- (d) 1.5% SiO$_2$ Nano
- (e) 2% Al$_2$O$_3$ Nano
- (f) 2% SiO$_2$ Nano
Figure 6. Von Mises (MPa) for Sockets with Al₂O₃ and SiO₂ Nano-materials for sample S₃.
a. 0.5% Al₂O₃ Nano

b. 0.5% SiO₂ Nano

c. 1% Al₂O₃ Nano
d. 1% SiO₂ Nano

e. 1.5% Al₂O₃ Nano
f. 1.5% SiO₂ Nano

g. 2% Al₂O₃ Nano
h. 2% SiO₂ Nano
**Figure 7.** Von Mises (MPa) for Sockets with Al₂O₃ and SiO₂ Nano-materials for sample S₄.

- a. 0.5% Al₂O₃ Nano
- b. 0.5% SiO₂ Nano
- c. 1.5% Al₂O₃ Nano
- d. 1.5% SiO₂ Nano
- e. 2% Al₂O₃ Nano
- f. 2% SiO₂ Nano

**Figure 8.** Deformation for Socket (mm) with Al₂O₃ and SiO₂ Nano-materials for sample S₁.
Figure 9. Deformation for Socket (mm) with Al₂O₃ and SiO₂ Nano-materials for sample $S_2$. 
Figure 10. Deformation for Socket (mm) with Al$_2$O$_3$ and SiO$_2$ Nano-materials for sample $S_3$. 

a. 0.5% Al$_2$O$_3$ Nano 

b. 0.5% SiO$_2$ Nano 

c. 1.5% Al$_2$O$_3$ Nano 

d. 1.5% SiO$_2$ Nano 

e. 2% Al$_2$O$_3$ Nano 

f. 2% SiO$_2$ Nano
Conclusions
From this work, the following conclusions can be drawn:
1. The numerical technique can be used efficiently to evaluate the stresses, deformation and stiffness to weight ratios for socket structures with different Nano-material incorporations.
2. The effect of SiO$_2$ Nano-material reinforcement, on mechanical properties was greater than the effect of Al$_2$O$_3$ Nano-materials in terms of improvement in stress levels, and the stiffness to weight ratio.
3. The stress and deformation developed in the socket decreased with increases in the volume fraction of Nano-materials used due to the increased stiffness.
4. The effect of SiO$_2$ Nano-materials was generally greater than that of Al$_2$O$_3$. Thus, the best composite for socket lamination, (2Perlon+2Kevlar+1Perlon+2Carbon+1Perlon+2Kevlar+2Perlon) could be combined with various volume fractions of SiO$_2$ Nano-materials.

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