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ENHANCED MECHANICAL PERFORMANCE OF PROSTHETIC FEET USING NANOMATERIAL-REINFORCED COMPOSITE LAMINATES

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ABSTRACT

Prosthetic feet are frequently manufactured using composite laminates to balance strength, weight, and comfort. Since these structures undergo varying stresses during gait, optimizing their mechanical properties is critical. This study investigated the influence of nanomaterial reinforcement on stress distribution in composite foot prostheses composed of carbon fiber, Kevlar, and Perlon. A mathematical model was employed to determine the effective modulus of elasticity, while finite element analysis was used to evaluate Von Mises stress, strain, and deformation. The suggested foot was analyzed in the case of heel strike. Results showed that incorporating SiO_2 nanoparticles at a 2.5% weight fraction improved the proposed layer sequence. (1Perlon+2Carbon+1Kevlar+4Perlon+1Kevlar+2Carbon+1Perlon) achieved the most significant improvements, reducing stress by 50.36%, strainby61.64%, and deformation by 35.50%. Al_2O_3 nanoparticles provided slightly lower but comparable performance. Overall, nano-reinforced composites demonstrate potential for developing lighter, stronger prosthetic feet that improve durability and patient comfort.

KEYWORDS

Laminated Composite, Nano, prosthetic foot, Numerical Technique.

1. INTRODUCTION:

The human body depends on the feet to provide support and maintain balance during standing and locomotion. The loss of a foot significantly reduces an amputee's ability to perform everyday activities, particularly walking(Resan, et al., 2011). The primary purpose of a prosthesis is to restore or enhance the functional abilities of individuals with disabilities. However, current prosthetic feet do not accurately replicate the complex biomechanical characteristics of the natural human foot (Mohammed, S.K. and Mohammed, A.H., 2021).

Modern prosthetic foot designs fall short of replicating the true attributes of a normal human foot. The human foot is one of the most complex structures of the body, providing a high degree of stability and mobility. It not only supports the entire body weight but also performs multiple functions, including extension, compression, torsion, bouncing, shock absorption, and friction (Mohammed, H.S. and Salman, J.M., (2020). It is essential to understand the recognized classifications of manufactured prosthetic feet, as multiple systems exist; the most significant among them are SACH, single-axis, multi-axis, dynamic response, energy-storing, microprocessor-controlled, non-articulated feet (Braddom, R.L., 2011).

Recently, several researchers have studied prosthetic feet designed and manufactured from polyethylene. (Saad, M.,2018), discusses various properties of composites and their applications in orthopedic implants, which are relevant to the development of prosthetic devices. Research has progressed to include feet made from composite materials consisting of several layers of fibers. Investigating the mechanical properties of composite structures through approaches such as the incorporation of various nanomaterials is essential to achieving optimal performance (Aljashaami, et al., 2024, Al-Amiri et al., 2025). However, improvements in the mechanical properties of composites reinforced with conventional fibers are typically limited to less than 20%. In contrast, the incorporation of nanoparticles has been shown to enhance the mechanical properties of composite materials by more than 30% (Kadhim, F.M., et al., 2019). (Jweeg, M.J. and Ameen, S.H., 2011)., examined the dorsiflexion lifespan and angle of prosthetic feet fabricated from different laminated composite materials. The study involved the experimental fabrication and testing of foot prototypes, complemented by theoretical analysis for validation. **(**Jweeg, M.J., et al. 2018), Additionally, they calculated the stresses and distortions brought on by temperature changes and examined how the artificial foot behaved according to these conditions. The study included experimental investigations to ascertain the mechanical properties of the materials used in the construction of the foot structure, in addition to computational analysis through the finite element method to assess stress distribution as well as deformation under various temperature conditions Also**,** (Takhakh, A.M., 2018)., The study examined a partial foot prosthesis by evaluating the stresses and mechanical properties of its composite materials through both finite element analysis and experimental testing.

(Hussain, H.S. and Takhakh, A.M., 2017), A theoretical and experimental comparison was carried out between conventional plastics (polyethylene and polypropylene) and composite materials (perlon, glass fibers, and hybrid carbon fibers) for partial foot prostheses. Composite materials were chosen for their strength, light weight, and low cost. Tensile, fatigue, and flexural tests showed that composites exhibited superior mechanical performance, with GF-hybrid CF and PCP demonstrating the longest fatigue life compared to traditional plastics. (Abbas, S.M., 2018), focused his experimental research on evaluating the mechanical properties of nine laminated composite types, including N-glass, fiberglass, carbon fiber, and perlon, used to manufacture a partial foot socket via a vacuum pressure system, using lamination as the 80:20 matrix. His results showed improving the mechanical characteristics and lowering expenses. (Chiad, J.S., et al. 2017), investigated the improvement of mechanical properties in materials for lower limb orthotic prostheses by utilizing nanomaterials, selecting the best lamination materials according to yield strength, bending stress, fatigue behavior, and ultimate stress. Lastly, at the same year, Al-(Waily, et al., 2020), Incorporating 2% volume fraction of nanoparticles (Nano Al_2O_3 and Nano SiO_2) significantly enhanced the mechanical and fatigue properties of composite prosthetic materials. The study used experimental methods combined with artificial neural networks (ANN) to analyze and predict results, showing that nanoparticle reinforcement improves strength, mechanical performance, and fatigue limits, with Nano SiO_2 providing the most notable improvements—up to approximately 30%. (Khalaf, N.J. et al. 2024), enhancing the mechanical properties of Ankle–Foot Orthoses (AFOs) by incorporating titanium nanoparticles into composite materials. The research employed Response Surface Methodology (RSM) to optimize manufacturing parameters, specifically the number of Perlon fiber layers and the percentage of titanium nanoparticles in the resin. A survey conducted by the Rehabilitation Technology Research Unit at Monash University examined 12 different prosthetic foot models (Rihs, D. and Polizzi, I., 2001). To perform demanding activities, such as sports, military operations, and other physically intensive tasks. The diverse needs and rehabilitation goals of amputees have spurred advances in prosthetic technology. This foot design was chosen for the current study because of its comfort, light weight, and ability to be manufactured from woven composite materials such as carbon fiber, Kevlar, and Perlon. These fibers are generally used in prosthetic limbs because they are light and have high strength, especially carbon and Kevlar.

This work aims to calculate the distribution of stresses in an artificial foot designed from a composite material reinforced with twelve woven fibers. This arrangement (1Perlon+2Carbon+1Kevlar+4Perlon+1Kevlar+2Carbon+1Perlon) was suggested sequence. Applying finite element method using ANSYS software, the suggested foot was analyzed statically in heel strike situation for the foot weighting (82) kg, this stage has been tested because it is the most important because in this case the human weight has the greatest impact on the foot. After the mathematical calculation method is done by programming equations in Excel 2020 to calculate the values of the elastic modulus of the layers according to the proposed sequence. Nanomaterials (SiO_2 and Al_2O_3) were added in weight fractions up to 2.5% each. Then a comparison is made to obtain the best percentage of improving properties and the lightest weight of the prosthetic foot, which leads to more comfort for the amputee patient when walking.

2. RESEARCH METHODOLOGY:

In this work, the suggested sequence of twelve woven layers (1Perlon+2Carbon +1Kevlar+4Perlon+1Kevlar+2Carbon+1Perlon) is used to manufacture an artificial foot. The number12 of layers was taken depending on the most previous researches (Takhakh, A.M., 2018, Jweeg, et al.,2012, Al-Waily, et al.,2020, Abbas, E.N., et al.,2020, Alewi, A.A., 2018). This number of layers achieved the best mechanical properties through their practical and theoretical experiments. Therefore, these studies were relied upon in selecting the number 12 for the fiber sequence and then the material properties of this composite material are enhanced by adding different weight fractions of the nanomaterial up to 2.5% for each of SiO_2 and Al_2O_3. In theoretical calculation, the material properties composite materials with and without nanomaterial are calculated as a first step for computing stress distribution in an artificial foot. In order to simulate the loading of an artificial foot, several points must consider:

2.1. Requirements of the prosthetic foot:

Amputees often appear distorted and irregular in walking compared to the natural gait in terms of step length, imbalance and slow walking, the reason for this is that the presence of muscles in the natural limb gives sufficient flexibility to walk that the prosthetic limb lacks also there is a difference between the natural limb and the prosthetic limb in weight in addition to other physiological reasons The work and function of the prosthetic foot can be described as follows (Al-Zubaidi, D.H.J., 2022):

1- Correctly adjusting the movement and standing of the amputee.

2- Transfer of body weight and additional loads from the area of contact of the body with the prosthesis limb to the ground.

3- Energy storage and release capabilities help in making walking easy.

2.2. The prosthetic foot's geometry:

In this work, the prosthetic foot's geometry is illustrated in Fig.1, design adapted from a previous study as in (Almudhaffar, M.M.A., 2020).

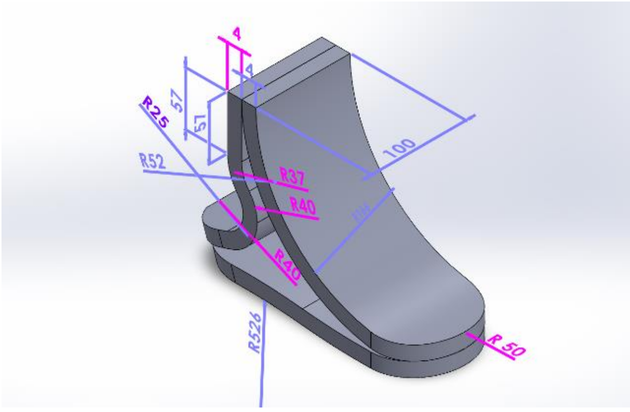

Fig. 1. The geometry graphing of foot.

2.3. Composite materials and the foot's structural design.

The mechanical properties of resin and woven fibers are listed in Table 1 that produce the following mechanical properties of the adopted sequence: modulus of elasticity = 16.78 GPa.; Poisson ratio 0.22 and density =1180 (kg/m^3). The following calculation method is adopted in this work:

2.3.1. Calculation the Mechanicals Properties of Woven Fabrics:

The composite material's mechanical characteristics can be determined once the characteristics of both fibers are known, (Carbon Fiber Kevlar Fiber, Perlon) and the matrix, all fibers are woven at 0°-90°, so it is an isotropic mat fiber both density and mass, in addition to the mechanical's property. Two orthogonal directions are used to weave the fabrics: the warp and the weft. When these weaves are interlaced at a 90° cross-section, where the warp and weft are perpendicular, the bidirectional fabric's modulus of elasticity can be computed using the formula (Gay, D. and Hoa, S.V., 2007).

$$E_1w = kE_1 + (1-k) \quad (1)$$

$$E_2w = (1-k) + kE_2 \quad (2)$$

$$E_t = \frac{1}{2}E_1 + \frac{1}{2}E_2 \quad (3)$$

$$v_{12}w = [v_{12}/k + (1-k)\, E_1/E_2] \quad (4)$$

Where $k = \frac{n_1}{n1+n2}$, n_1= quantity of warp yarns in one meter, n_2= quantity of fill yarns in one meter. E_1, E_2w, and $v_{12}w$: mechanical characteristics of the textiles woven in directions 1 and 2 were evaluated.

$$W_{R=}0.55 * \rho_R * a * b * h \quad (5)$$

$$W_{f=}0.45 * \rho_f * a * b * t \quad (6)$$

Where is: W_R is weight of lamina risen, h=4mm is total thickness of the layers, t=0.333 thickness of each layer.

$$\text{Density of each layer} = 0.55 * \rho_R + 0.45 * \rho_f \,. \quad (7)$$

The mechanical properties of the adopted sequence are calculated using the following method. The layers are 4 mm thick, and the laminate consists of [twelve] as in the Fig. 2. From the mechanical properties of each layer, Each material's elastic modulus and poison ratio (E_1, E_2,… E_{12}), (υ_1, υ_2,…. υ_{12}) as in Table 1. Next, using Excel 2020 programming to determine the elastic modulus, the layer stacking was chosen based on the computational equations. Since the height of the i[th] layer equals z_i, the following equation displays the expression for z_i, (Guo, X-G., et al., 2017).

$$z_i = \sum_{j=1}^{i} h_i \quad (8)$$

The effective Young's modulus E should be used in place of the Young's modulus E_i. The following formula is used to get the i[th] layer's moment of inertia, or I_i, with regard to the laminated layers' neutral axis

$$EI = \sum_{i=1}^{n} \bar{E}\, I_i \quad (9)$$

$$I_i = \frac{1}{3} W \left({z_i}^3 - {z_{i-1}}^3 \right) \quad (10)$$

$$I = \frac{1}{12} W h^3 \quad (11)$$

Where W is the width, and h height the layer.

Table 1. Properties of Materials Utilized in This Research (Jweeg, et al., 2012)

Materials Used	Densities(g/cm^3)	Young's modulus GPa	Poisson ratio
The Perlon Fiber	1.083	2.6-3	0.39
The Kevlar Fiber	1.44	67.7	0.4
The Carbon Fiber	1.76	122.5	0.3
Lamination resin	1.04	3.24	0.35

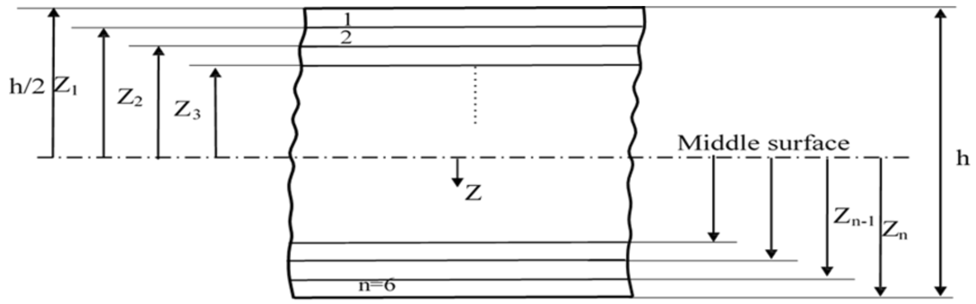

Fig. 2: The geometry of an n-layered laminas (Al-Waily, M., 2004).

2.3.2. Nano-Composite Materials used in this Work

Nano alumina (Al_2O_3) and nano silica (SiO_2) are used to enhance the mechanical properties of Lamination resin (Jweeg, M.J., et al., 2021) of the prosthetic foot. The nanomaterial (alumina or silica) was added to Lamination resin with volume fraction (0.5, 1, 1.5, 2.0 and 2.5) %. The enhanced mechanical properties of Lamination resin due to adding the nanomaterial were listed in Table 2.

Table 2. Material properties used with different Nanomaterial volume fractions

Nano Alumina Material (Al_2O_3)		Nano Silica Material (SiO_2)	
Nano Volume Fraction (%)	**E (GPa)**	**Nano Volume Fraction (%)**	**E (GPa)**
0	16.78	0	16.78
0.5	17.34	0.5	17.92
1	18.42	1	19.12
1.5	19.83	1.5	20.33
2	20.88	2	21.74
2.5	22.47	2.5	23.87

3. FINITE ELEMENTS ANALYSIS:

Finite Element Analysis (FEA) is a numerical method for solving complex problems, with ANSYS offering applications from simple linear static to advance nonlinear dynamic analysis (Al-Ansari, L.S., et al., 2012.) Engineering problems are efficiently solved using software such as ANSYS and SOLIDWORKS, which apply finite element analysis (FEA). In this study, ANSYS 2020R2 was used to obtain stress distribution contours through three main analysis steps (Almudhaffar, M.M.A., 2020).

- Creating the geometry model and generating the mesh.
- Applying boundary conditions and obtaining the solution.
- Review results.

3.1. Graphing of the Geometry:

Model of a 59-year-old, 82 kg woman with right below-knee amputation, created in SolidWorks 2020 and exported to Parasolid (.x_t) format Fig. 1.

3.2. Types of Elements:

ANSYS SOLID185, with eight nodes and three degrees of freedom per node, models 3D solids, supporting large strain, deflection, and irregular geometries. Element thickness is specified after selection Fig. 3. (Najm, A.A., 2013).

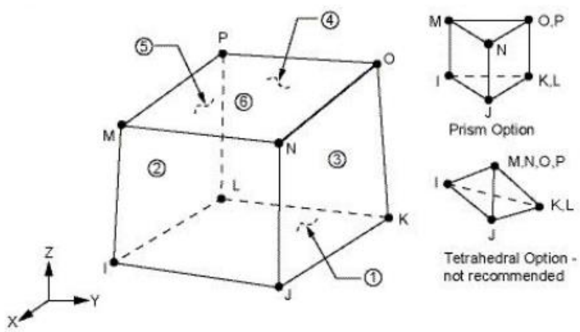

Fig. 3: solid element (najm, a.a., 2013).

3.3. Convergence test:

The optimal mesh size was determined via a mesh convergence study. Refining from coarse to fine meshes, maximum stress values were recorded Table 4. Once the element count reached

17,209, the maximum stress stabilized at 28.85 MPa, indicating mesh independence and convergence, consistent with other studies (Surapureddy, R., 2014), Fig. 4. Further refinement offered no significant benefit but increased computational time.

Table 4 Mesh Convergence: Number of Elements vs. Maximum Stress

Iteration	Number of elements	Number of nodes	Max.Von Mises stress (MPa)
1	4657	11829	19.79
2	5714	14633	18.61
3	7917	21121	28.60
4	10933	28947	27.88
5	17209	42931	28.85
6	28880	74330	30.77
7	58196	148711	40.40
8	85390	218225	47.60
9	102451	325458	28.80
10	123587	45872	28.78

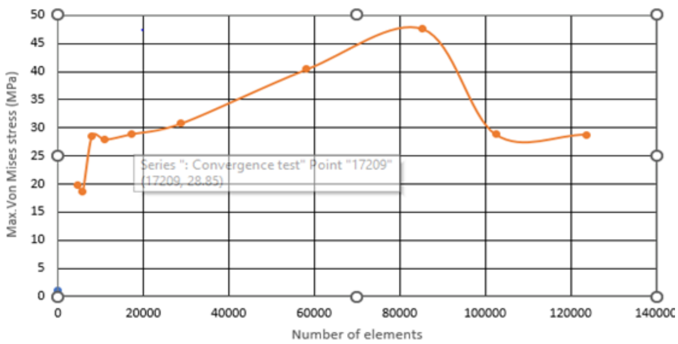

Fig. 4. Convergence test

3.4. The Boundary Conditions:

The load can be applied via PREP7 or the Workbench static structural tree. The analysis type and options must be specified before initiating the finite element solution, based on the loading conditions Fig. 5. For the case study, the heel strike load was applied per ISO 10328, corresponding to a ground reaction force of 965.3 N for an 82 kg subject. (Almudhaffar, M.M.A., 2020).

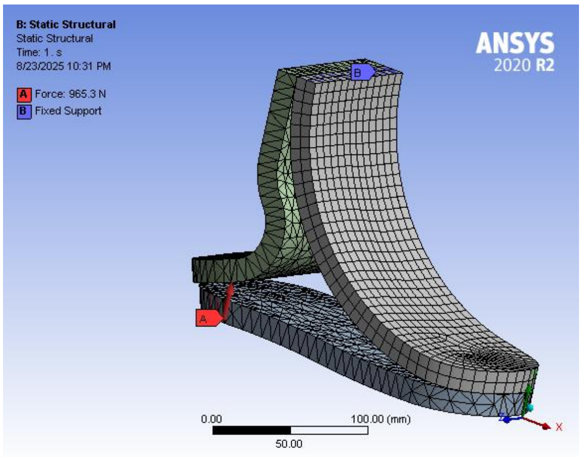

Fig. 4. Convergence test

4. RESULTS AND DISCUSSION

The prosthetic foot was analyzed statically using FEM (ANSYS) under an 82 kg load, evaluating total deformation, elastic strain, and von Mises stress, with a comparison between nano-alumina and nano-silica composites.

Fig.6,7&8 show the distributions of von Mises stress, equivalent elastic strain, and total deformation for the prosthetic foot made of composite without nanomaterials, using the adopted sequence (1 Perlon +2 Carbon + 1 Kevlar + 4 Perlon +1 Kevlar + 2 Carbon + 1 Perlon). The highest von Mises stress appears near the contact area between the foot components due to stress concentration caused by the shape effect.

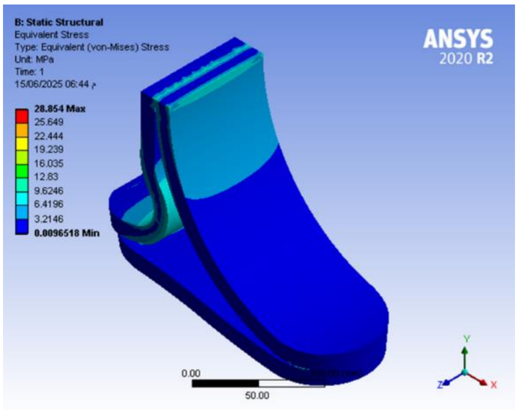

Fig.6. Max. von Mises Stress Distribution in the Foot without Nanomaterial

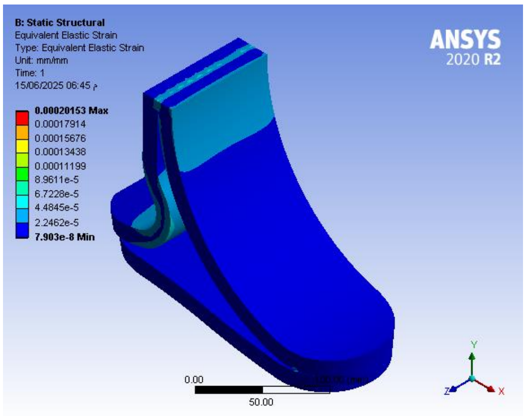

Fig.7. Equivalent Elastic Strain Distribution in the Foot without Nanomaterial

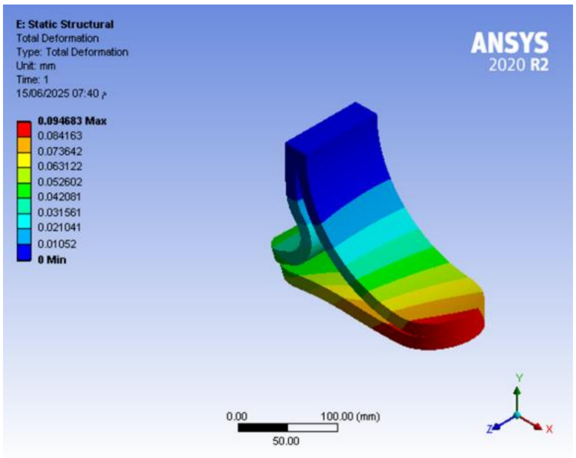

Fig.8. Total Deformation Distribution in the Foot without Nanomaterial

In Fig.9,10 and 11 the comparison between the distribution of von-misses stress, Equivalents Elastic strain and Total deformations when the nanomaterial is used to improve the properties of Lamination resin. The results vie volume fraction of nanomaterial is listed in Table 5,6 and 7, Fig.12, 13 and 14.

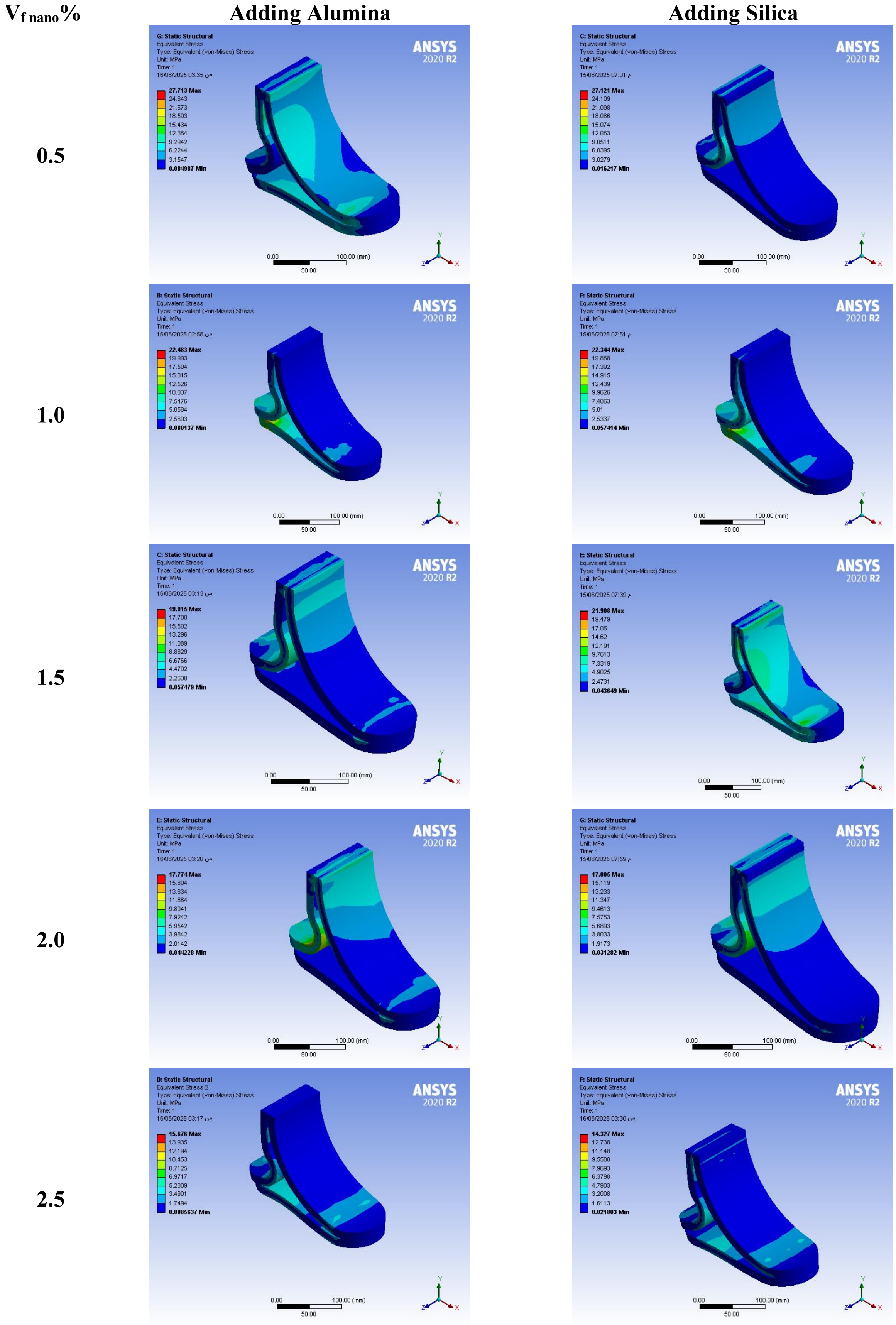

Fig. 9. Von Mises Stress Distribution in the Foot with Different Nanomaterial Volume Fractions Using the Adopted Sequence.

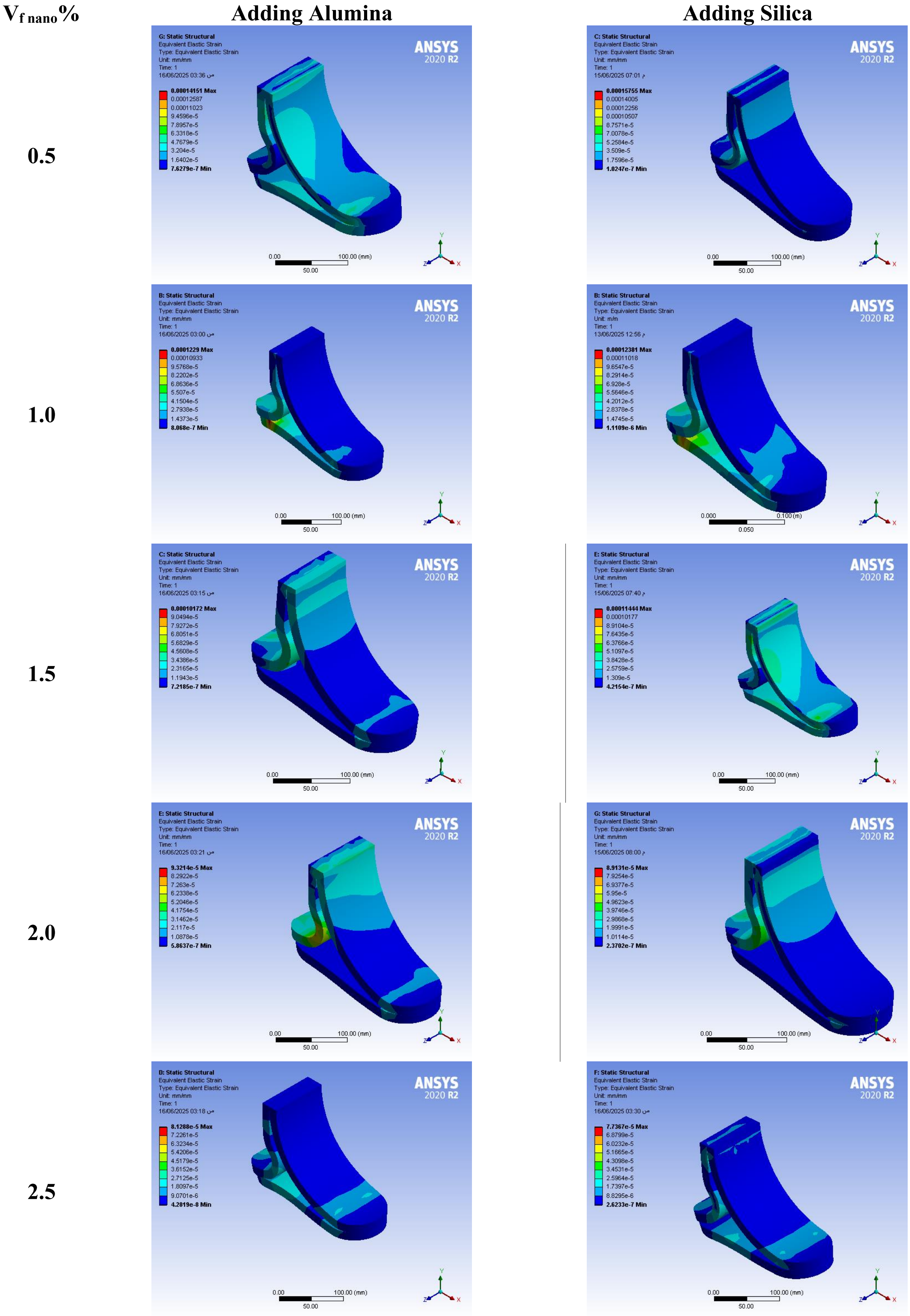

Fig. 10. Equivalent Elastic Strain Distribution in the Foot with Different Nanomaterial Volume Fractions Using the Adopted Sequence.

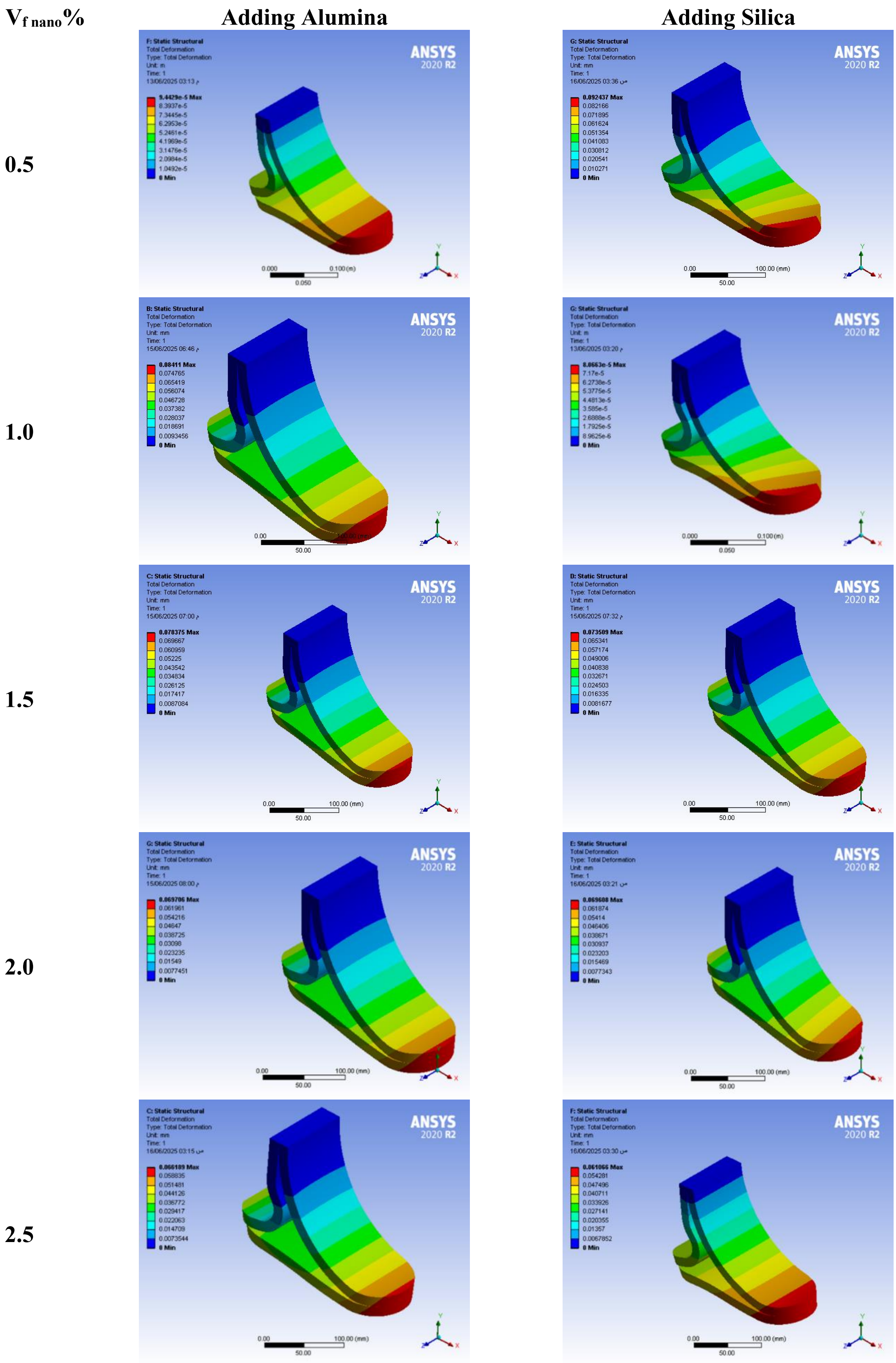

Fig. 11. Total Deformation Distribution in the Foot with Different Nanomaterial Volume Fractions Using the Adopted Sequence

Table 5 Maximum Von Mises Stress Variation with Nanomaterial Volume Fraction

Nano Volume Fraction (%)	Maximum Von-Misses Stress (MPa.)	
	Alumina	Silica
0	28.85	28.85
0.5	27.71	27.12
1	22.48	22.34
1.5	19.91	21.9
2	17.77	17.0
2.5	15.67	14.32

Table 6 Variation of Equivalent Elastic Strain with Nanomaterial Volume Fraction

Nano Volume Fraction (%)	Equivalent Elastic strain (mm/mm.)	
	Alumina	Silica
0	0.00020153	0.00020153
0.5	0.00014151	0.00015755
1	0.00012290	0.00012380
1.5	0.00010172	0.00011444
2	0.00009321	0.00008913
2.5	0.00008128	0.0000773

Table 7 Variation of Total Deformation with Nanomaterial Volume Fraction.

Nano Volume Fraction (%)	Total deformation (mm.)	
	Alumina	Silica
0	0.094683	0.094683
0.5	0.094429	0.092437
1	0.084110	0.086630
1.5	0.078375	0.073509
2	0.069706	0.069608
2.5	0.066189	0.061066

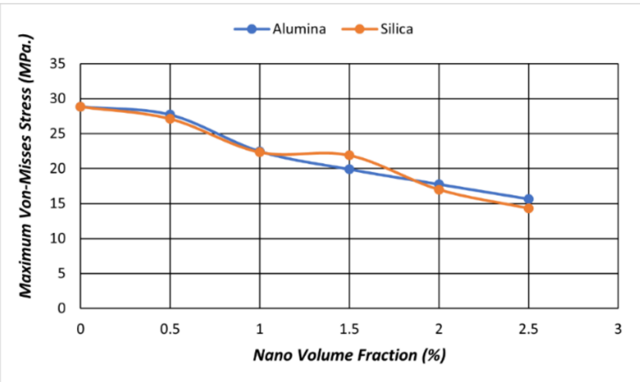

Fig.12. Variation of Max. Von-Misses Stress Due to Volume Fraction of Nanomaterial.

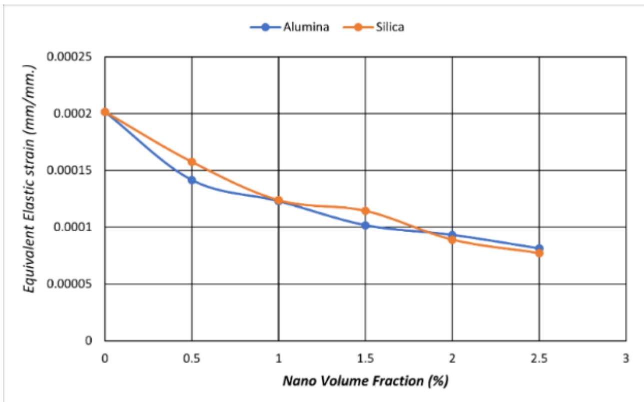

Fig.13. Variation of Equivalent Elastic strain Due to Volume Fraction of Nanomaterial.

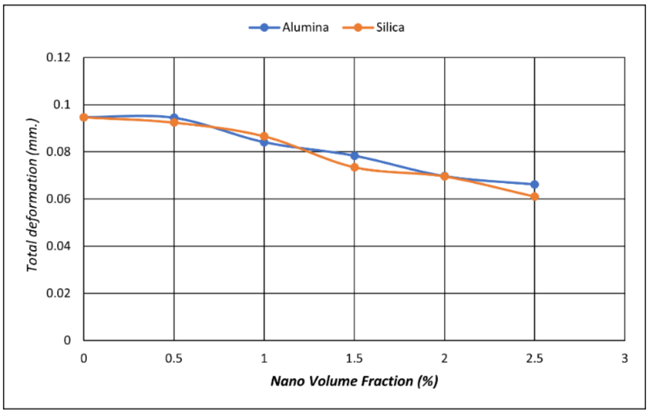

Fig.14. Variation of Total deformation Due to Volume Fraction of Nanomaterial.

The addition of nanoparticles increases the durability and strength of the prosthesis, which in turn increases the reliability of the prosthesis under actual load conditions. The use of nanomaterials and their effect on the prosthesis improves functional performance, (Jweeg, M.J., et al., 2021). Incorporating nanomaterials was found for reduce the stresses induced; elastic strain and deformation in the foot. Adding nanomaterials to prosthetic feet reduces weight and cost and improves performance (Khalaf, N.J. et al. 2024). The proposed nano-reinforced artificial foot (sequence: 1 Perlon + 2 Carbon + 1 Kevlar + 4 Perlon + 1 Kevlar + 2 Carbon + 1 Perlon) for an 82 kg patient exhibits lower maximum stress values compared to similar studies on feet for patients under 80 kg, where the maximum stress was reported as 34.126 MPa (Almudhaffar, M.M.A., 2020). The maximum stress values in this study are lower than in previous works, with 15.67 MPa for 2.5% Al_2O_3 and 14.32 MPa for 2.5% SiO_2 reinforcement. This reduction is attributed to two factors: the greater number of layers used (12 layers) and the strengthening effect of the nanomaterials. Consequently, the mechanical performance of the proposed artificial foot is improved compared to earlier studies.

1. Stress was decreased by 50.36% with reinforcement using SiO_2 Nano-materials and by 45.68 with reinforcement with Al_2O_3.

2. Equivalent elastic strain decreased by 61.64% with SiO_2 nanomaterial reinforcement and by 59.66%with Al_2O_3 reinforcement.

3. Total deformation decreased by 35.5% with SiO_2 nanomaterial reinforcement and by 30% with Al_2O_3 reinforcement.

4.1. Case Study on Verification:

To verify the validity of results and numerical analysis of afoot, a case study must be conducted close to the foot specification. The foot was drawn with the same dimensions and analyzed using Ansys in heel strike case, at force 941 N and the weight of patient 80 kg a below-knee amputation, and Modulus of elasticity (E) 2.103Gpa. Fig. 15 show the results were similar to those from the thesis (Almudhaffar, M.M.A., 2020) and numerical analysis. Table 8. showing the results obtained from the numerical analysis for this case.

Table 8 The comparison results.

Von-Mises Stresses	34.126MPa	Case Study (Almudhaffar, M.M.A., 2020)
Von-Mises Stresses	35.966 MPa	Verification Case Study.

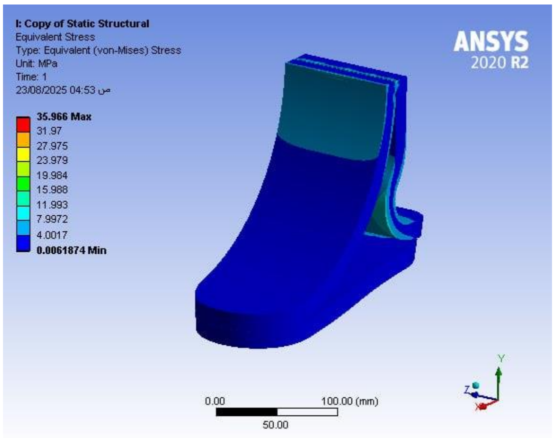

Fig.15. The Verification Case Study's Equivalent (Von-Mises) Stress for an 80 kg heel strike

5. CONCLUSIONS AND RECOMMENDATIONS:

Based on the earlier talks, the findings outlined below is derivable as follows:

1. The numerical method effectively evaluates stress in foot models reinforced with nanomaterials.
2. SiO_2 nano-materials significantly influence mechanical properties, with the greatest composite foot being mixed with different nanomaterial volume percentages.
3. Increased nanomaterial volume reduced foot stress due to increased stiffness.
4. Future research should investigate creep and fatigue behavior of prosthetic feet and crack development.
5. Analyze the stresses and strains for the two cases, heel strike and toe off.

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