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Theoretical Analysis of a New Design of Dynamic Prosthetic Foot

Diyaa H. J. Al-Zubaidi[1] and Mohsin Abdullah Al-Shammari[2]

[1]University of Baghdad, College of Engineering, Mechanical Engineering Department, Iraq,
[2]University of Baghdad, College of Engineering, Mechanical Engineering Department, Iraq,

Abstract

Due to the increasing demand and urgent need for prosthetic limbs for amputees, especially prosthetic feet, it has become necessary to expand the design and use of composite materials in the production of prosthetic feet to meet the needs of amputees, providing comfort and ease of use. In this work, a new dynamic prosthetic foot with the ability to store and release energy will be designed using composite material which consist of the carbon fiber with lamination resin. The mechanical properties and the S-N curve of the composite material were experimentally calculated by testing samples made of carbon fibers with lamination resin. These properties are entered into the numerical solution using the ANSYS program to design the proposed prosthetic foot for several attempts to reach good results that perform the desired purpose. The results represented by the equivalent stress, directional deformation, the number of fatigue life cycles and the safety factor will be calculated, in addition to knowing the mass and volume of the foot.

The effect of mechanical properties on the results in the numerical solution was identified, then compare the numerical results with each other. Where the results were acceptable, especially the safety factor is greater than 1, the angle of dorsiflexion was 7.88^0, and the number of life cycles exceeded 1000000 cycles.

This proposed new design of the foot can be used to serve the amputees, as this foot has the ability to store and release energy to give smoothness and comfort in walking and movement.

Key Words: Prosthetic foot, Carbon fiber, Mechanical properties, S-N curve, Safety factor.

1. Introduction

Prosthetics can be defined as devices or equipment that replace missing organs and their functions or complement the work of these organs within the skeletal system of the human body. These devices can be linked to the body either through orthopedic surgery or installed externally [1]. The main purpose of the device - the foot - the prosthesis is to simulate the function of the human body as closely as possible to help the person do his job well even though prosthesis can't replace the missing part [2]. It is necessary for the prosthesis to perform the desired purpose, especially the user's comfort and acceptance in addition to durability, reliability when walking, ease of use, endurance for the longest period while allowing the practice of different activities and subject to several other factors that have an impact on the user's comfort and ease of movement, and that comfort and movement are linked to three main factors which: the patient, prosthetic ingredients and prosthetics limb [3]. Several factors should be viewed as while choosing the correct foot for your way of life. These factors incorporate your amputation grade and level, weight, age, foot size, action level, aims and occupational requirements [4]. Before starting the process of manufacturing the prosthetic foot, it is necessary to know the type of amputation, the type of foot to be manufactured, and the functions that are required to be performed. These limitations and types will be addressed for each case, after the design of the limb is completed, it will be manufactured according to the specifications and dimensions required according to the patient's condition and the suitability of the prosthesis when used.

Several researchers have manufactured different prosthetic feet and many tests have been conducted, in 1975, Daher R.L. [5] presented a comprehensive investigation in which several types of SACH feet about nine types were subjected to periodic testing to identify the durability of the components and evaluate the design of the foot until failure occurred. At 1987, Wevers H. W. and Durance J. P. [6] dynamically loaded the prosthesis across the transtibial and the foot together. It was found that the results obtained by them are similar to the results obtained by Daher in the previous research in terms of quick wear and structural failure of the prosthetic foot through 100,000 cycles or less. While in 1990, Toh S. L. et al [7] used the simple fatigue machine to avoid complex loading. It does not simulate gait but only applies periodic vertical loads to the forefoot and heel. Both the toes and the heel were tested and examined applying periodic sinusoidal axial loads that peak at 1.5 times from body weight and at a frequency of (2 Hz) when it reaches 500,000 revolutions. The load and constant deviation tests were conducted between periodic cycles to detect and know the changes in the mechanical properties of the foot. As well, in 1993, Lehmann J. F. et al. [8, 9] performed an analysis using a static loading machine to determine the relationship between the applied load and the deflection of the prosthetic foot, and explain how the amputee gait cycle will be affected by the difference in response, they concluded that the SACH heel that presses more as it is softer than others. After this, at 2007, Muhsin J. Jweeg et al. [10] have designed and manufactured a new prosthetic foot that differs from SACH foot in terms of characteristics and shape using polyethylene, it was found that the new foot is better than the SACH foot due to several advantages, such as its longer operational life, better return energy, and the dorsiflexion angle of the foot more suitable for the patient's comfort. Also, in 2009, R. Figueroa and C.M. Müller-Karger [11] used numerical programs (finite element FE) in the process of designing the prosthetic foot, after analyzing the dynamic energy return (DER) of the prosthetic feet, the results indicated that the new prosthetic foot is similar to the Axtion foot and Niagara foot in terms of its ability to dynamic energy return (DER), also for the proposed foot with high displacement in the softer regions, especially in a toe region that provides a greater spring to store energy at the standing phase and release it when starting the swing phase by providing a forward thrust that helps walking and running easily. And in 2011, Muhsin J. Jweeg and Sameer Hashim Ameen [12] calculated the dorsiflexion angle and the life of the ankle-foot for one foot made of perlon-carbon fiber-acrylic (PCA) materials and another foot made of polypropylene (PP), theoretically and experimentally. At 2013, Vibhor Agrawal et al. [13] presented a design for a new prosthetic foot called Proprio's foot, which is controlled by a microprocessor for patients who have one-sided transtibial amputation (TTA), they did several practical tests for a number of patients for several days and practice different activities, especially climbing and descending stairs. So, Heimir Tryggvason et al. at 2017, [14] have modeled and simulated the missing limb by designing and manufacturing an articulated prosthetic foot, where the design was made using the finite elements (FE) and the characteristics of the stiffness and durability of this foot and its dimensions were determined, then manufactured. Finally, in 2019, Siamak Noroozi et al. [15] investigated the mechanical properties of a new dynamic prosthetic foot called Ossur Flex- Run that has the ability to store and release energy, it was found that the new foot has the ability to enhance the response and generate a natural and permanent leap forward without any an excitation force at its natural frequency, this is a unique dynamic and engineering property of this foot. Too, Samer A Kokz et al. at 2021, [16] presented a design for the prosthetic ankle foot joint, this foot simulates the natural human foot in terms of size, shape, and angle of movement by imitating natural walking on sloping surfaces.

In addition to the presence of other researchers, they manufactured feet of different specifications using various composite materials and extracted good results, but in this work, a new shape of dynamic feet will be manufactured using a suggested combination of composite materials, the proposed foot will be tested in order to estimate its life cycles of the foot, also the angle of dorsiflexion will be calculated numerically.

2. Numerical Solution

In the current paper, the Finite Element Method (FEM) is utilized for the numerical modeling of the new dynamic prosthetic foot proposed in this work. The analysis was performed using ANSYS 16.1 program, where it is necessary to select the input data and modeling, [17-22], and then extract the output data.

2.1. The Input Data

In order to start designing the new prosthetic foot, it is necessary to identify two determinants, namely the geometry of the foot and the properties of the materials used in the manufacture of the foot, [23-28], as follows:

2.1.1 Determination the Geometry of the Foot

The foot will be designed with the new geometry of the proposed dynamic prosthetic foot shown in its general geometry as in figure (1), which differs in terms of shape and functionality from the widely available prosthetic foot, where this proposed foot will be arched in a circular, semi-circular, ellipse or oval in the heel region has the ability to store energy when the heel strike and release this energy when the heel is raised to provide additional energy that helps to walk smoothly and faster, [29-34].

It is linked to this arch from the top by a vertical beam that is connected to the bottom of the leg or shank, and from the bottom is linked to a convex arch in the middle of the foot is similar for the natural foot shape, then the region of the toe-off of the feet that are contact the ground.

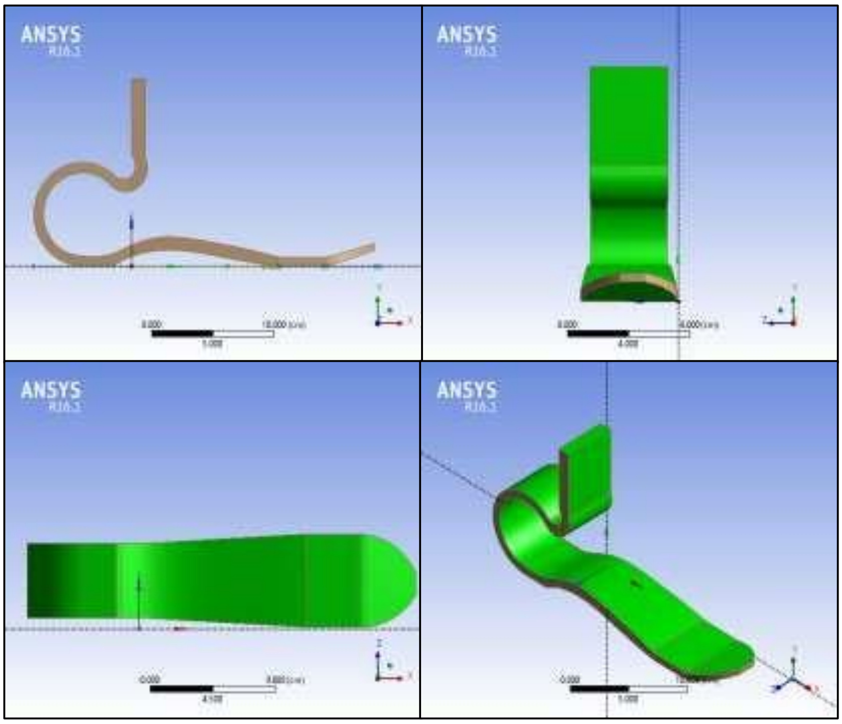


Figure 1: The geometry of the proposed foot by ANSYS.

2.1.2 Material Properties

To complete the required information in the ANSYS program after completing the required geometry, it requires calculating the values of the mechanical properties of the material such as density, Young's modulus, tensile yield strength, tensile ultimate strength, S-N curve, etc. [35-40]. All these values were obtained experimentally by casting several samples using the same the material that will enter into the design of the new foot, [41-46], which is made of a functionally graded material four-layer carbon fiber woven with lamination resin (composite material) using a tensile test device according to the international classification (ASTM D-638), and a fatigue test device. The results of the mechanical properties of the samples that were found in practice are as in table (1) as for the properties of the alternating stress mean stress as shown in table (2), the drawing of the relationship between the numbers of life cycles with the stress (S-N Curve) through fatigue test as in figure (2).

Table 1: The mechanical properties**.**

No.	**Property**	**Symbol**	**Value**	**Unit**
1	**Density**	ρ	1310	kg/m^3
2	**Young's modulus**	E	20	GPa
3	**Poisson's ratio**	ν	0.25	
4	**Tensile ultimate strength**	σ_ult	212	MPa
5	**Yield strength**	σ_Y	210	MPa
6	**Volume fraction**	$V.F$	28 %	

Table 2: Stress- number of life cycle relation for carbon fiber with lamination resin.

No.	**N (Cycles)**	**Alternating Stress (MPa)**
1	10	208
2	15	197
3	25	187
4	100	158
5	125	155
6	135	154
7	400	135

8	1000	120
9	3500	105
10	4250	103
11	10000	92
12	20000	85
13	30000	81
14	100000	70
15	200000	65
16	250000	63
17	350000	60.5
18	500000	58
19	600000	57
20	1000000	53

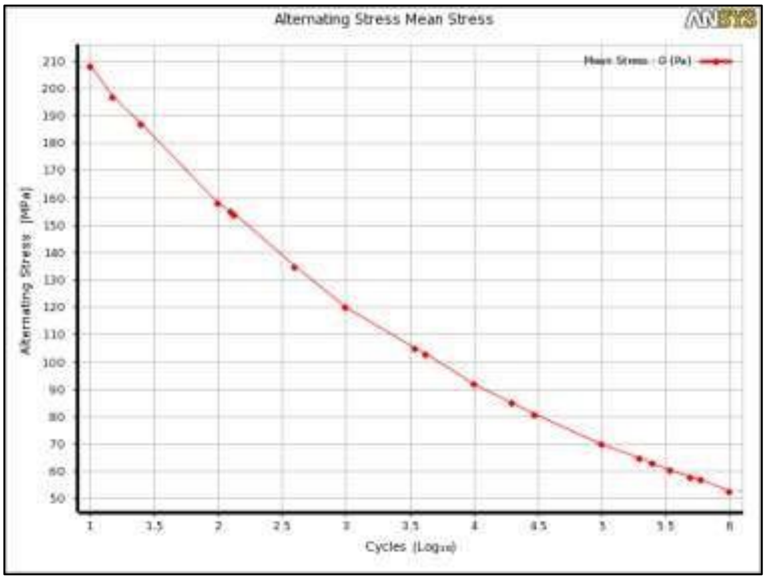


Figure 2: S-N curve for carbon fiber with lamination resin.

2.2.The Modeling

To complete the modeling process of the proposed model, the shape of the element, the number of the mesh must be determined, the boundary conditions of the support must be known, in addition to the value, location and direction of the applied forces, [4752], as follows:

The geometry of the element will be determined according to the geometry of the foot, where the geometry of the element is determined by the type of (hexahedron) as in figure (3), it is the best type of mesh as it gives a consistent and regular mesh and with the same measurement that can be used in static structural applications, [53-58].

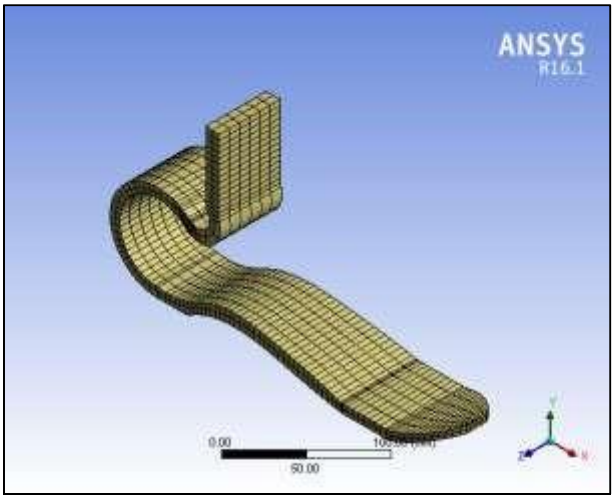


Figure 3: Mesh uses a hexagonal element.

The best mesh size will also be determined and the number of elements will be selected through a mesh check according to each result, [59-64], it is assumed that the maximum stress is chosen with the number of elements, where it is noted that the maximum stress is constant ($\sigma_{max} = 90.1\ MPa$) when the number of elements reach to (20125 element), which is considered to reach the point of a mesh independent size point is reached, it represents a steady state stage (S.S) as in figure (4).

Figure 4: Convergence test.

The designed foot is fixed from the top and is free from the bottom, which is an simulation of the natural foot, as it is connected to the bottom of the leg on one side and is free to move on the other side from the side of the toes, [65-70], as shown in figure (5).

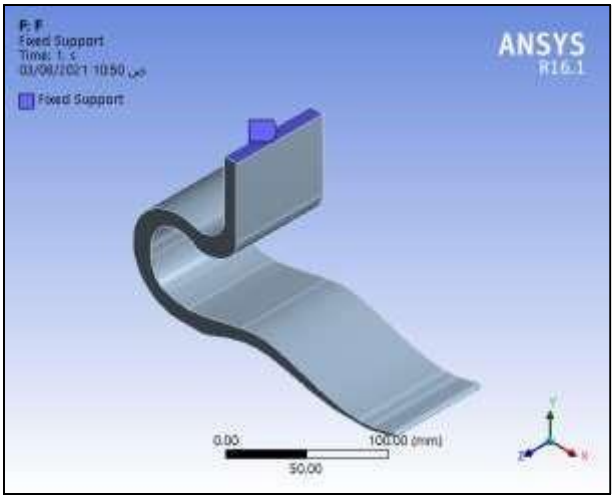


Figure 5: The foot with fixed supported.

2.3.The Loading (Applied Force)

The forces acting on the foot represent the ground reaction forces on the foot, [71-76], it was assumed that the body mass of an amputee is (m = 80 kg), which represents (W = 784.8 N), which is the average weight for adults and is common often. The gait cycle consists of two phases: the swing phase, and the stance phase, which is divided into three periods: the heel strike, the mid stance and the toe off, the stance phase was drawn graphically as in figure (6),

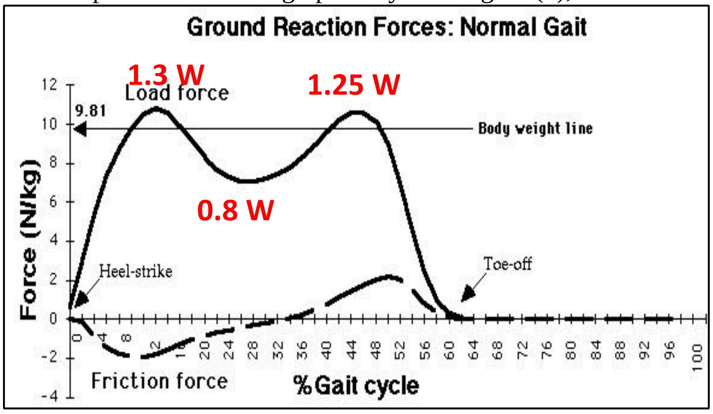


Figure 6: Diagram of the gait cycle graphically [77].

Where the force at the heel region (F_1) represents 1.3 of the body weight, while the force at the tips of the toes (F_2) represents (1.25) of the body weight.

$$\boldsymbol{F_1 = 1.3 \times W = 1020.24\ N} \quad \text{and} \quad \boldsymbol{F_2 = 1.25 \times W = 981\ N.}$$

Figure (7) shows that the first force is inclined at an angle of (+20^0) from the vertical axis and that the second force is inclined at an angle of (-15^0) from the vertical axis experimentally, where the components of the force are:

$$(F_{1x} = F_1 \times sin\ 20 = 348.943\ N \rightarrow), \qquad (F_{1y} = F_1 \times cos\ 20 = 958.712\ N \uparrow)$$
$$(F_{2x} = F_2 \times sin\ 15 = 253.9\ N \leftarrow), \qquad (F_{2y} = F_2 \times cos\ 15 = 947.573\ N \uparrow)$$

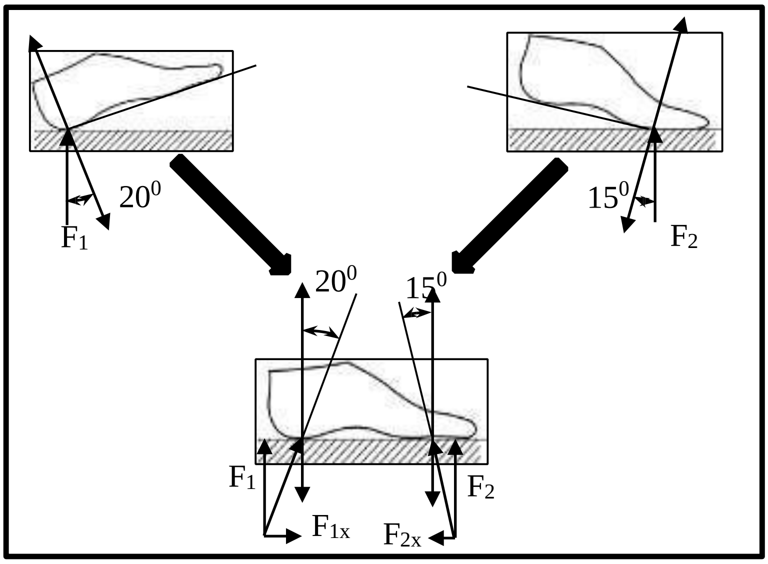


Figure 7: Angles of foot inclination.

Therefore, the forces will be applied in the ANSYS program (F1 = 1020.24 N) and (F2 = 981 N), each force according to its angle of inclination as shown in figure (8)

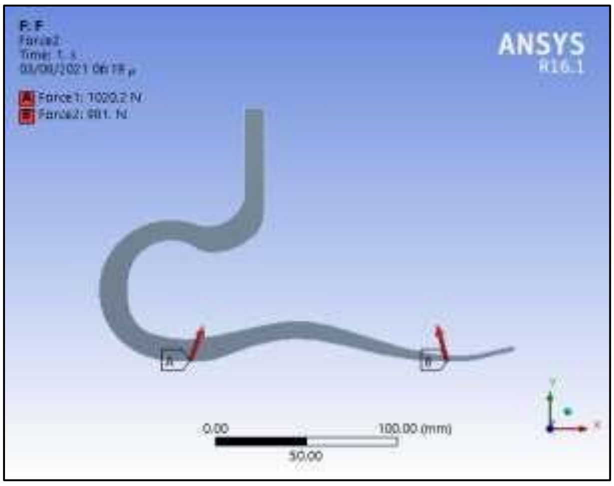


Figure 8: Forces applied on the foot.

2.4.The Results (Output Data)

After completing the design mesh for the proposed foot and applying the required forces, the outputs required in this work will be determined. The important main variables to be calculated are the safety factor (S.F) and the directional deformation (D.D) towards the y-axis, in addition to calculating the stress and strain values**.**

3. Results and Discussion

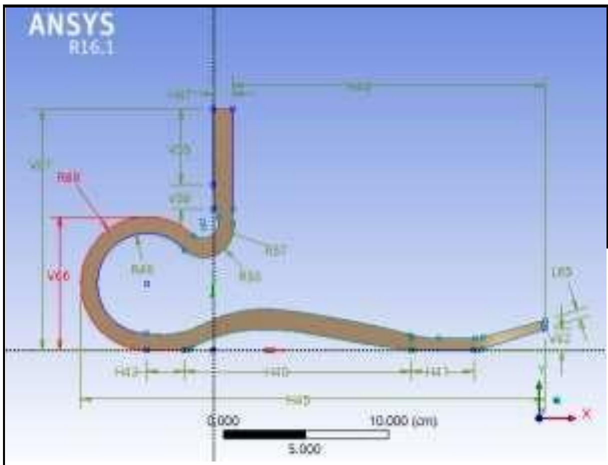
The results of the designs of the proposed foot shapes are calculated numerically and these results are compared with each other to reach the optimal shape of the prosthetic foot.

3.1.Design of the Foot Numerically and Compare the Results

The new dynamic foot is designed according to the proposed geometry, which gives ease of movement in walking and has the ability to store and release energy, where the thickness and dimensions of the foot will be changed to reach the optimal geometry that achieves a safety factor greater than one (S.F > 1), the foot mass not exceeding (500 g), the dorsiflexion angle within the range acceptable and the foot size is proportional to the natural foot.

After completing the inputs to the ANSYS program that was experimentally obtained through the examination of samples, the proposed initial geometry of the foot was determined with the assumption of the applied forces and the type of supported, the results will be calculated in detail for each case where the regions of weakness that will fail first are known in the designed foot to increase the thickness to the minimum that achieves the required results or some dimensions are changed to ensure that the stresses are distributed almost equally on the whole foot for several attempts until reaching to the optimal design for the new foot, the foot designs and results will be explained in steps as follows:

Step 1: The proposed initial geometry for the foot has been drawn with its dimensions shown as in figure (9) below:



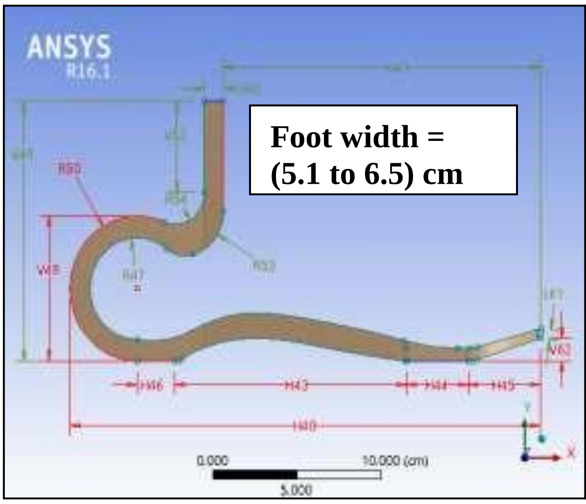
Foot width = (5.1 to 6.5) cm

Dimensions: 16	
H40	13.697 cm
H41	3.7872 cm
H43	2.2486 cm
H45	28 cm
H46	18.85 cm
H47	1.15 cm
L65	0.50385 cm
R48	3 cm
R57	1 cm
R58	1.8 cm
R68	4 cm
V55	4.5275 cm
V56	1.4725 cm
V62	1.25 cm
V66	8 cm
V67	14.447 cm

Figure 9: Foot geometry with dimensions for step 1.

The main results of the previous figure were calculated, where it was noted that the maximum equivalent stress is very high, the maximum directional deformation in the y-axis is very large compared to the length of the foot, the minimum number of life cycles is very few and the minimum safety factor in some regions of the foot is less than 1 (S.F<1), where it will be treat the weak points of the foot by increasing its thickness in the next step.

Step 2: The thickness of the designed foot in step (1) was increased in weak regions, especially the increase in the thickness of the back arch of the foot and the increase in the thickness of the regions between the two radii (R53 and R54), as shown in figure (10):



Dimensions: 16	
H40	28 cm
H41	18.85 cm
H42	1.15 cm
H43	13.805 cm
H44	3.6789 cm
H45	4.2671 cm
H46	2.2486 cm
L61	0.55454 cm
R47	2.8 cm
R50	4 cm
R53	2.5002 cm
R54	1.75 cm
V48	14.348 cm
V49	8 cm
V52	5.0563 cm
V62	1.25 cm

Figure 10: Foot geometry with dimensions for step 2.

Step 3: The length of the designed foot in the previous figure (10) will be reduced in the previous step from (28 cm) to (23 cm), and the width of the foot is fixed with a width of (6 cm) with the same thickness of the foot gradation for all regions as in figure (11):

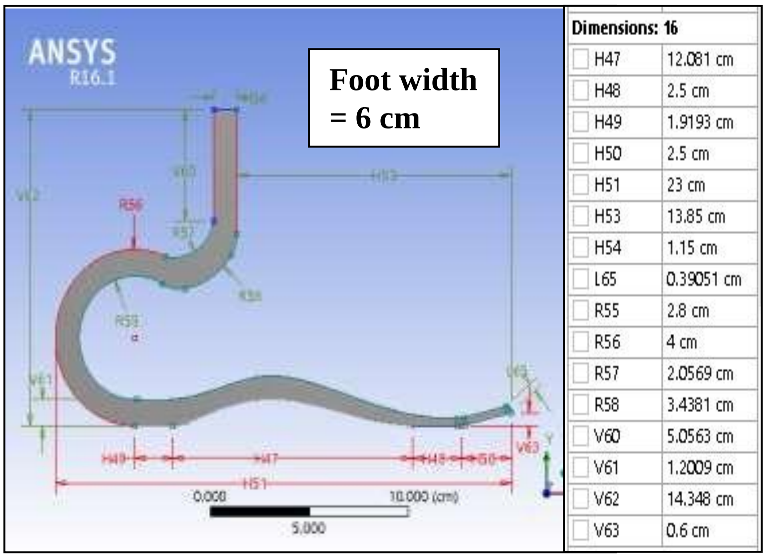
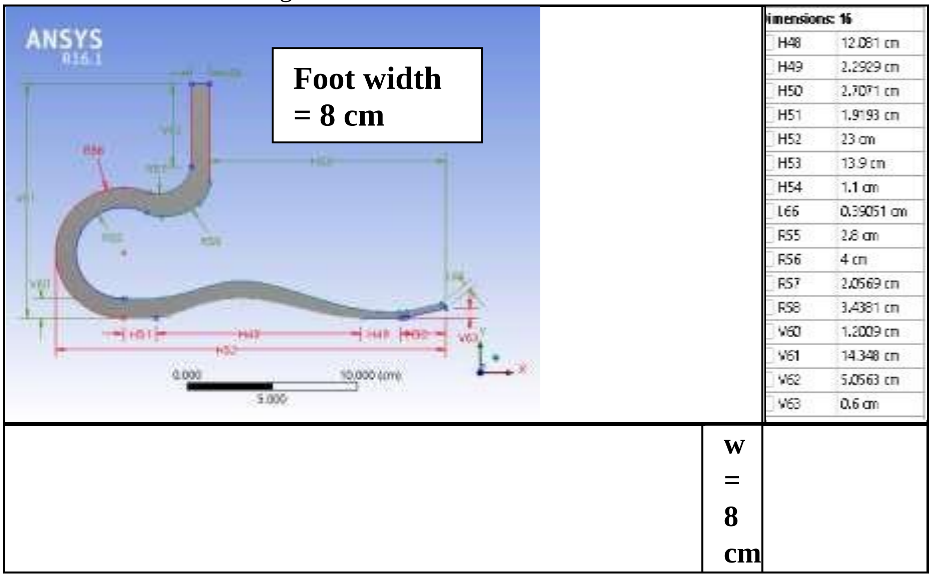


Figure 11: Foot geometry with dimensions for step 3.

When checking the results of this step, it was found that the maximum equivalent stress and the directional deformation in them are a little more than the acceptable values, but the minimum number of life cycles and the safety factor are still below the required values, which are ($N_{min} = 10^6$ and S.F > 1).

Step 4: The width of the foot was increased from (6 cm) to (8 cm) as shown in figure (12), with the geometry of the foot remaining fixed with the same length and the same thickness gradation for the foot.



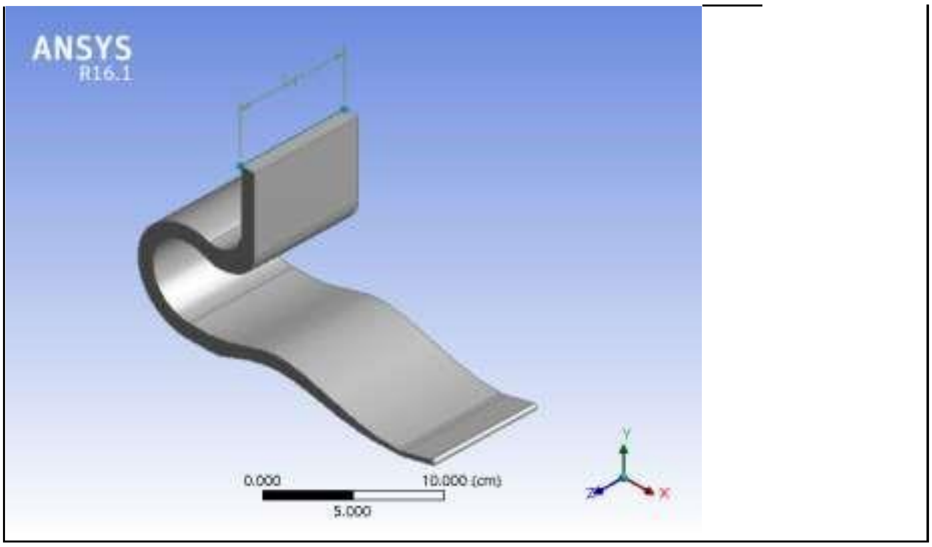


Figure 12: Foot geometry with dimensions for step 4.

In this step, it is found that the results that were calculated for the last foot geometry, which is (8 cm) wide, are acceptable to a large degree, but it needs some simple change of the foot geometry, which will take place in the end step.

Step 5: A simple modification will be made in the geometry of the foot so that the thickness of the weak region, which is in the region at the end of the foot in the middle of the two arches, will be increased with a decrease in the width of the foot from (8 cm) to (7.5 cm), so the shape of the inner arch was changed from semi-circular to semi-oval as in figure (13) to ensure that the thickness of the weak region is increased exclusively without the regions remainder.

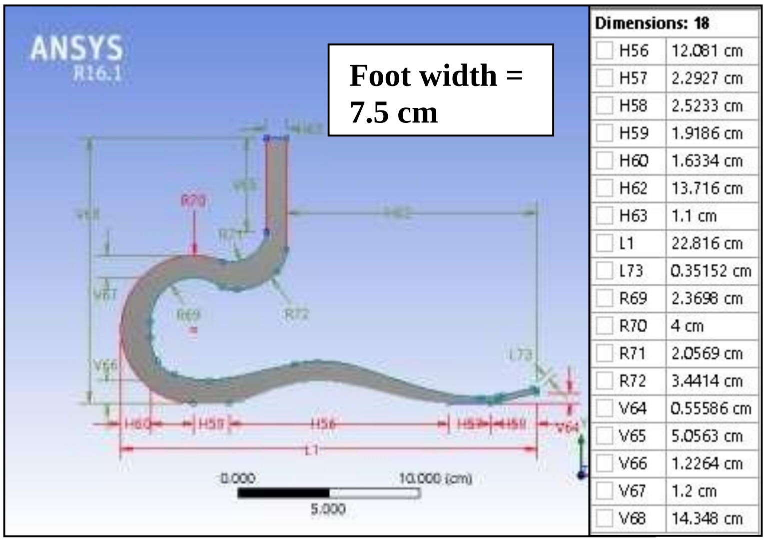


Figure 13: Foot geometry with dimensions for step 5.

Figure (14) shows that the results of this design in step (5) are perfectly acceptable with a design with minimum foot volume (V = 332.67 cm^3), and minimum foot mass (m = 435.8 g),

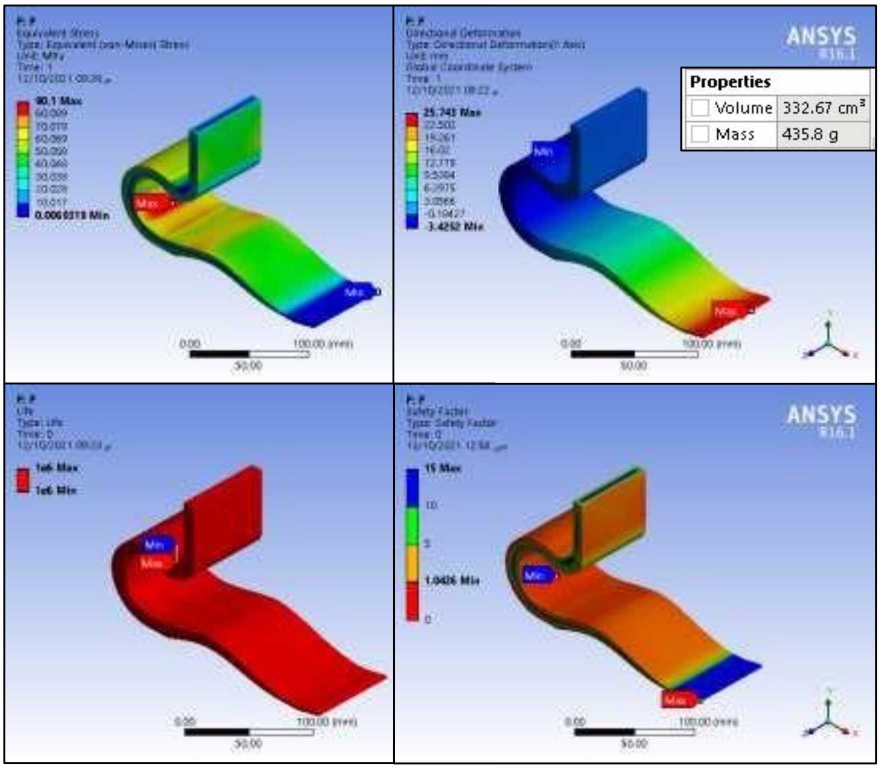


Figure 14: Foot Results for step 5.

Where the maximum equivalent stress is ($\sigma_{max.Equi} = 90.1\ MPa$), the maximum directional deformation on the y-axis is (y = 25.743 mm), the minimum number of life cycles is greater than (N >10^6), and the minimum safety factor greater than (S.F > 1), Therefore, this geometry of the foot shown in the above figure (13) was considered the final and ideal geometry and design of the foot.

These designs mentioned in the previous five steps are considered a summary of dozens of designs, but the concentration has been limited to on these important designs briefly and in order to avoid prolongation, to know the results of the previous five steps, the results and some dimensions and properties of the foot for each step will be tabulated as shown in table (3):

Table 3: Summary of the five steps.

State	No	Variable \ Step	Step 1	Step 2	Step 3	Step 4	Step 5
Dimensions (cm)	1	Foot length	28	28	23	23	22.816
	2	Foot width	5.1~6.5	5.1~ 6.5	6	8	7.5
	3	Foot height	14.447	14.348	14.348	14.348	14.348
	4	Inner arc radius	3	2.8	2.8	2.8	2.3698
	5	Outer arc radius	4	4	4	4	4
	6	Thickness ave.	0.95	1.01	1.06	1.06	1.08
Prope	7	Foot vol. (cm^3)	254.28	289.53	251.24	335.49	332.67
	8	Foot mass (g)	333.1	379.28	329.12	439.49	435.8
Results	9	$\sigma_{max.equi.}$(MPa)	258.55	185.31	131.07	95.819	90.1
	10	$D.D_{max.}$ (mm)	117.68	65.512	42.541	31.862	25.743
	11	$N_{min.}$	0	68.843	7754.8	283333	>= 10^6
	12	Minimum S.F	0.32736	0.50693	0.7167	0.8833	1.0426

Finally, the dorsiflexion angle (α) of the foot is calculated numerically using the following equation

$$\alpha = tan^{-1}\left(\frac{y}{L_{eff.}}\right)$$

Where (y) is the maximum directional deformation in the vertical direction, and ($L_{eff.}$) is the effective length of this foot and their values were calculated numerically as follows:

(y = 25.743 mm and $L_{eff.}$ = 186 mm).

$$\therefore \quad \alpha = tan^{-1}\left(\frac{25.743}{186}\right) = 7.88^{\circ}$$

4. Conclusions

The most important conclusions obtained in this paper can be summarized, as shown below:

1. The mass and volume of the prosthetic foot in its optimum geometry is considered acceptable and within the normal range or less than it, which provides the necessary requirements as it is considered to be of high acceptability.
2. This prosthetic foot, gave good results such as bearing different weights, stresses and forces, acceptable dorsiflexion angle, number of life cycles with a long life ($N > 10^6$), and achieving the required safety factor in addition to its low cost compared to other prosthetic feet.
3. The proposed new geometry of this foot gives flexibility in use and has the ability to store and release energy as it is of a dynamic type in which movement is smooth and easy to walk.

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