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Analytical and experimental investigations for the pressure distribution between the stump and the Syme's prosthesis

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Abstract
This study aims to suggest an analytical indirect approach to find the pressure distribution at the stump-socket interface in the Syme's prosthesis. The results are compared with those obtained experimentally using the F-socket device. Finally, a finite element model was built to analyze the effect of the internal pressure on the socket. The analysis was made in the SOLIDWORKS subprogram in both static and dynamic solutions. The results show that there is a great agreement between the experimental and analytical results so it is possible to dispense the results of the F-Socket device in cases of the unavailability of it and depend on the analytical solution.

Keywords: Syme; Prosthesis; SOLIDWORKS; F-Socket device.

1. Introduction

When a person loses its ability to walk because of an accident or a disease, he needs an alternative to restore this grace. Lower limb prosthesis is used for that purpose, the most substantial parameter in this case is the fitting between the cut section of the leg (stump) and the socket [1]. In the area between stump and socket, pressure is usually developed, the immoderate amount of this pressure causes many problems like tissue damage and/or an improper gait pattern [2]. The underlying soft tissues and skin of the stump are not accustomed to weight bearing; so, there is a danger of degenerative tissue ulcer in the stump due to constant or repetitive peak pressure which is applied by the Transtibial socket [3]. Although the great advances in the prosthesis field during the last decades, there are many Transtibial amputees pain due to the pressure ulcers with the use of prostheses, and other times, skin problems lead to chronic infection, which may necessitate re-amputation. This will stop using the prosthesis for a long time, which decreases the daily activities of prosthesis users and the quality of life [4]. Therefore, it is so important to specify that load. Two ways were used for that which are [5]: direct measure performed exactly in the interface, which used several types of sensors like hydraulic sensors and the indirect measure of the external properties of the socket, where load cells and strain gauge place on a specific zone of the external surface of the socket [6]. Marinus Naeff et al. [7] calculated the peak pressures at the interface between the thigh and a simulated above-knee (AK) socket brim with the using a flexible sensor. This work aims to determine the load distribution between the socket and stump experimentally and analytically. It represents a complementary work to a previous research on the same subject [8] and the procedure of selecting the material presented in [9].

2. Residual limb-socket interface pressure

In the Jweeg et al. work [8], four groups of composite materials were tested, their details were shown in Table1. The higher strength group (group D) was chosen to manufacture a syme prostheses for a subject (male) with 53 years old have Syme's amputations in the right foot, tall = 172 cm and 91 Kg weight. The direct measurement approach was selected to find the interface pressure between the residual limb and socket, by using Tekscan F-Socket system, Figure 1a and b show the subject during the test. Tekscan system employed medical sensors 9811B, which are force sensitive variable resistors and combined with the sofiware package named Research Foot 6.70 permissions to measure the value of the pressure at the considered point. The sensors work within a pressure between 0 and 517 kPa, and because of their small thickness (0.1mm) and flexibility, transducers can be placed inside the socket, directly in contact with the skin, without any effect on the pressure measurements and, without hurtful the socket. Each sensor stripe includes 96 sensels positioned on a 6x16 matrix with a density 0.6 sensels/cm^2, Figure 1c shows the shape of the F-socket sensor. The test was achieved as follows,

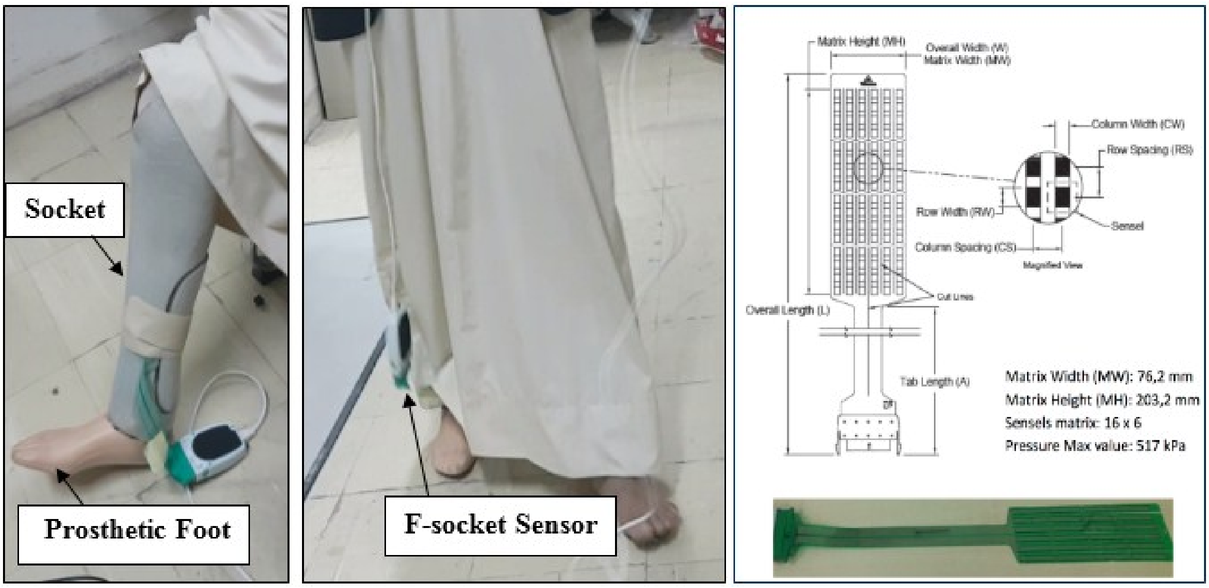
1- The sensor was placed at the end of the stump (the end of the cut-out opening region) then, the patient is allowed to wear the socket.

2- The patient starts to move, in the meantime the device record the average pressure value during his walking.

3- The test was repeated another two times along the length of the socket.

Table 1. Laminates sequence of the composite material [8].

Group Name	Types of layers	Additives	Total Number of layers
Group A	2 Perlon fiber + 1 Carbon fiber + 2 Perlon fiber + 1 Carbon fiber + 2 Perlon fiber	None	8 layers
Group B	2 Perlon fiber + 1 Carbon fiber + 2 Perlon fiber + 1 Carbon fiber + 2 Perlon fiber	5 % date palm nuts powder	8 layers
Group C	2 Perlon fiber + 1 Carbon fiber + 2 Perlon fiber + 1 Carbon fiber + 2 Perlon fiber	10 % date palm nuts powder	8 layers
Group D	2 Perlon fiber + 1 Carbon fiber + 1 Perlon fiber + 2 Carbon fiber + 1 Perlon fiber + 1 Carbon fiber + 2 Perlon fiber	None	10 layers



(a) (b) (c)

Figure 1. (a, b) The subject during the F-Socket test (c) the shape of the F-socket sensor [5].

The results of the average pressure distribution of the patient were taken during its normal walking, the peak value of pressure was found near the foot (at the beginning of cut-out opening). Figure 2 shows the peak pressure for the subject through walking.

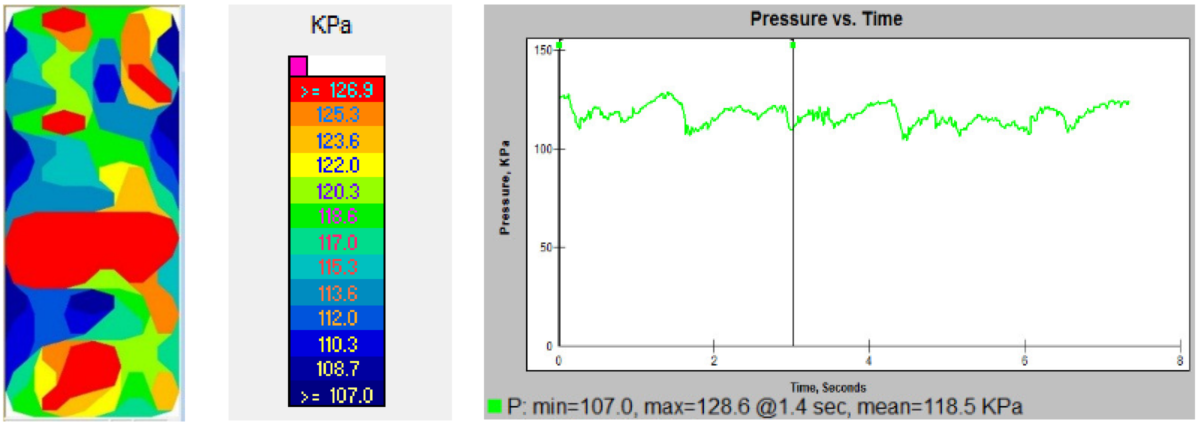


Figure 2. Peak pressure distribution from F-Socket device.

3. Analysis of stump-socket forces in the below – knee amputation

To determine the forces between the residual limb and the prosthetic socket, a simple model has been established and the following assumptions were considered [10]:

i. The socket shell would force the soft tissue of the limb into a conical shape.

ii. The internal bone was represented as a cylinder as shown in Figure 3.

iii. Tissues are elastic materials and behave as a spring support (F= Kd).

iv. The material is uniform, isotropic, linear and complete contact with the limb.

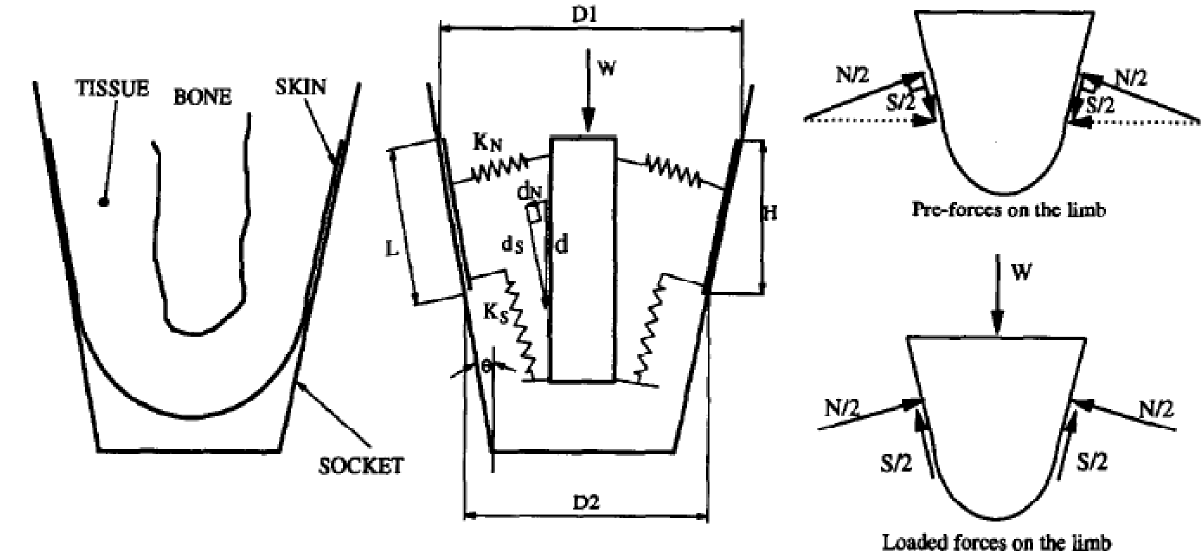


Figure 3. A simplified residual limb model [10].

The skin leftovers firm to the socket while the internal soft tissue is linked to the bone. The compressing and extending the skin and the soft tissue amid socket and bone led to transfer the skeletal forces to the prosthesis. There are two forces applied from the tissues, the first one was ‘perpendicular’ spring which is presumed to represent the support force produced by compression of the soft tissues perpendicular to the skin surface, while the second one is ‘tangential’ spring embodies the force produced by extending or shearing parallel to the interface. So, the perpendicular and tangential spring constant $K_{N,}K_s$ (respectively) can be calculated as follows [10],

$$K_N = \frac{EA}{t} \tag{1}$$

$$K_s = \frac{GA}{t} \tag{2}$$

where $G = \frac{E}{2(1+v)}$ and $A = \frac{L\pi(D_1+D_2)}{2}$, E is Young's modulus of soft tissue, G is the shear modulus, v is the Poisson ratio of soft tissue, t is the average thickness of soft tissue, A is the area of supporting surface of the skin, L is the length limb contacts with socket and D_1, D_2 are the socket diameters at the upper and lower side of the support surface respectively.

At the interface, it is assumed that there is a sufficient friction so as to stop the skin movement with respect to the socket shell, and this assumption will be modeled in the next calculation by addition certain pre-pressures. Generally, some pre-compression at the residual limb/prosthetic socket interface without loading, so it is assumed that the perpendicular spring is pre-compressed by a displacement of d_{N_o} and that the tangential spring had to be pre-compressed by d_{S_o}.

To achieve the vertical force balance condition represented on the socket [10], $N_o \sin\theta = S_o \cos\theta$ and by applying the spring law, the equation will be as follow: $d_{N_o} K_N \sin\theta = d_{S_o} K_S \cos\theta$ therefore: $d_{S_o} = \frac{K_N}{K_S} d_{N_o} \tan\theta$.

Where θ is the conical angle, and it is can be found from, $2\tan\theta = \frac{D_1 - D_2}{H}$, which gives $\theta = \tan^{-1}\frac{D_1 - D_2}{H}$

Now, the bone is forced by a vertical force W, which represents the body weight and the inertial force, which results in a vertical movement d. According to the geometric relationship shown in Figure 1, the perpendicular spring will maintain to be compressed by [10],

$d_N = d\sin\theta$ While the tangential spring may be extended by, $d_S = d\cos\theta$. So, the total normal (N) and shear (S) forces are given by,

$$N = K_N(d_{N_o} + d_N) = K_N(d_{N_o} + d\sin\theta) \tag{3}$$

And

$$S = K_S(-d_{S_o} + d_S) = K_S\left(-\frac{K_N}{K_S} d_{N_o} \tan\theta + d\cos\theta\right) \tag{4}$$

These two forces have to be balanced the weight (W), so

$$W = N\sin\theta + S\cos\theta \tag{5}$$

And by substituting Eq. (3) and Eq. (4) into Eq. (5) gives,

$W = K_N \sin\theta\, d_{N_o} + K_N d\sin^2\theta - K_S\cos\theta \frac{K_N\, d_{N_o}}{K_S}\frac{\sin\theta}{\cos\theta} + K_S\, d\cos^2\theta$ Or $W = K_N\, d\sin^2\theta + K_S\, d\cos^2\theta$

Therefore:

$$W = d\,(K_N \sin^2\theta + K_S\cos^2\theta) \tag{6}$$

Where

$$d = \frac{W}{(K_N \sin^2\theta + K_S\cos^2\theta)} \tag{7}$$

It is required to measure the capability of the anti-deformation the interface stiffness (K). The interface stiffness equals to the force acting on the bone to the vertical displacement of the bone relative to the socket shell. So, it consists of the geometry of the limb and elastic modulus of tissue [10].

$$K = \frac{W}{d} \tag{8}$$

By substituting Eq. (6) into Eq. (8) gives,

$$K = K_N \sin^2\theta + K_S\cos^2\theta \tag{9}$$

To guarantee that sliding will not occur at limb/socket interface, the no-slip condition must be achieved, which means that the shear force should be less than or equal to the maximum friction force, hence [10],

$$S \leq \mu N \tag{10}$$

Substituting Eq. (3) and Eq. (4) into Eq. (10) gives,

$$K_S\left(-\frac{K_N}{K_S}d_{N_o}\tan\theta + d\cos\theta\right) \leq \mu\, K_N\left(d_{N_o} + d\sin\theta\right) \tag{10a}$$

Or

$$K_S\left(-\frac{K_N}{K_S}d_{N_o}\tan\theta + \frac{W\cos\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)}\right) \leq \mu\, K_N\left(d_{N_o} + d\frac{W\sin\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)}\right) \tag{10b}$$

That means,

$$-K_N d_{N_o}\tan\theta + \frac{W K_S\cos\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)} \leq \mu\, K_N d_{N_o} + \frac{\mu\, K_N W\sin\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)} \tag{10c}$$

Or,

$$\frac{W K_S\cos\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)} - \frac{\mu\, K_N W\sin\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)} \leq K_N d_{N_o}(\mu + \tan\theta) \tag{10d}$$

Therefore,

$$\frac{W K_S\cos\theta - \mu\, K_N W\sin\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)} \leq K_N d_{N_o}(\mu + \tan\theta) \tag{10e}$$

Finally, we could find the d_{N_o} from the above equation, which equals to:

$$d_{N_o} \geq \frac{W K_S\left(\cos\theta - \mu\frac{K_N}{K_S}\sin\theta\right)}{K_S\left(\frac{K_N}{K_S}\sin^2\theta + \cos^2\theta\right)} \cdot \frac{1}{K_N(\mu + \tan\theta)} \tag{10f}$$

So, the pre-compressive displacement of the perpendicular spring is given by,

$$d_{N_o} \geq \frac{W}{K_N}\frac{\left(\cos\theta - \mu\frac{K_N}{K_S}\sin\theta\right)}{\left(\frac{K_N}{K_S}\sin^2\theta + \cos^2\theta\right)(\mu + \tan\theta)} \tag{11}$$

The average pre-pressure at skin/socket interface can be found by applying the pressure law which is equal to $\frac{Force}{Area}$, where the force represented by N_o, so the law will be [10]:

$$P_o = \frac{N_o}{A} \geq \frac{K_N d_{No}}{A} \tag{12}$$

Substituting Eq. (11) into Eq. (12) gives,

$$P_o \geq \frac{W}{A}\frac{\left(\cos\theta - \mu\frac{K_N}{K_S}\sin\theta\right)}{\left(\frac{K_N}{K_S}\sin^2\theta + \cos^2\theta\right)(\mu + \tan\theta)} \tag{13}$$

Now, the average pressure and shear stress acting on the limb surface could be calculated as follows [10],

$$P = \frac{N}{A} \tag{14}$$

Substituting Eq. (3) and Eq. (7) into Eq. (14) gives,

$$P = \frac{K_N}{A}\left(d_{N_o} + \frac{W\sin\theta}{(K_N\sin^2\theta + K_S\cos^2\theta)}\right) \tag{15}$$

While the shear stress is given by [10],

$$\tau = \frac{S}{A} \tag{16}$$

Substituting equation (4) into Eq. (16) gives,

$$\tau = \frac{K_S}{A}\left(-\frac{K_N}{K_S} d_{N_o} \tan\theta + \frac{W\cos\theta}{(K_N \sin^2\theta + K_S \cos^2\theta)}\right) \tag{17}$$

Now, the mathematical equations were programmed in MATLAB R2008a software. The interface stiffness, average pre-pressure, average interface normal stress and the average interface shear stress will be found immediately after running this program. Figure 4 shows the flowchart of the Matlab program.

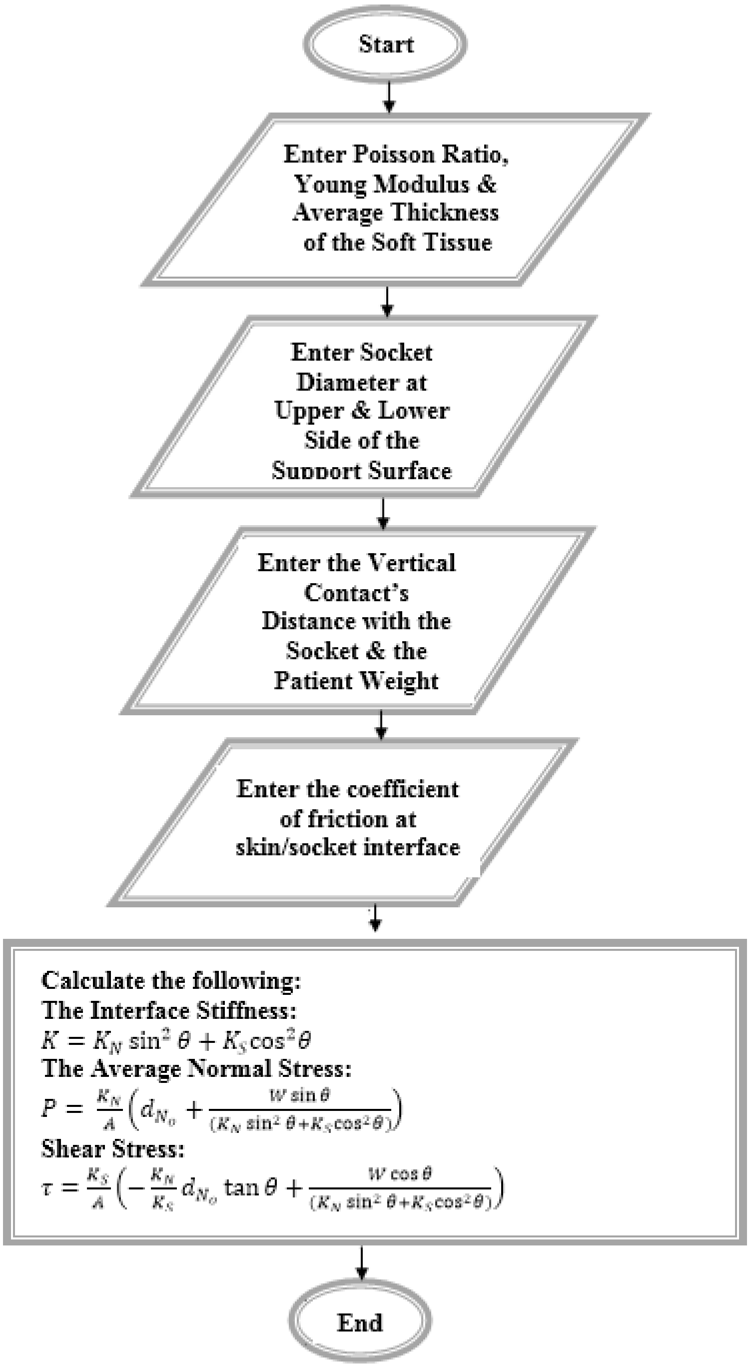


Figure 4. Flowchart of Matlab program.

In order to compare the mathematical result with the experimental one, MATLAB program was used at the same region that produces the peak pressure (at the beginning of cut-out opening; near the foot). So, running the program, the values of normal and shear stresses are obtained directly which are 137629.146697 Pa and 55051.658679 Pa and by taking the resultant stress the value is 148.231 Kpa. This value of stress in the static form and to do an accurate comparison it should be multiplied by the dynamic factor 1.2, so the resultant stress will be equal to 177.877 Kpa.

4. Computer methodology

Using SOLIDWORKS program (Version 2015), Syme's socket mode was created with the real dimensions of the subject. The model was created with an elliptical cut-out in the posterior position. The cut-out shape and type of material were obtained from [8] as shown in Figure 5. The meshing process was tested on the model. Finally, socket simulation is achieved to find the effect of the different internal pressures results on the socket.

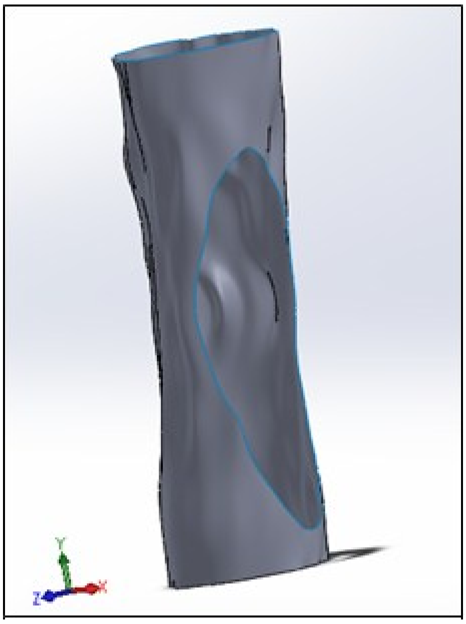


Figure 5. Syme's socket with elliptical cut-out.

5. Results and discussions

5.1 Load distribution

From the experimental and numerical methods, it is found that two values for the internal stump-socket stress, usually the mathematical result was reasonable. The percentage of discrepancy between the measured and calculated is as follows,

$$\text{Percentage of discrepancy} = \frac{\text{actual value} - \text{measured value}}{\text{actual value}} \text{X}100\% \tag{18}$$

So, the maximum percentage of the discrepancy is 27.7%, which is considered as an acceptable value.

5.2 Numerical results (SOLIDWORKS)

The sockets have been tested with two different internal loads, the first one resulted from the F-socket device while the second one that resulted from the mathematical equation.

5.2.1 Simulation using F-Socket Device Load

According to the result of the F-socket device which gives the internal stump-socket as a pressure-time curve, the simulation was done in two forms, the first one by applying the mean value in pressure sensor in the maximum pressure position (representing the end of the cut-out near the ankle) which is equal to 128Kpa and the solution by a static solution, while the second one by insert the pressure-time curve and solving it as a dynamic solution which is more accurate than the first one, the resulats of the dynamic simulation was taken at the last second of the test. Figure 6 shows the difference in the Von Mises stress between the static and dynamic simulation, while Table 2 shows the maximum deflections, strains, and stresses (components and principals) that generated in the two types of simulation. Figure 7 shows the maximum deformation happened in the two types of simulation.

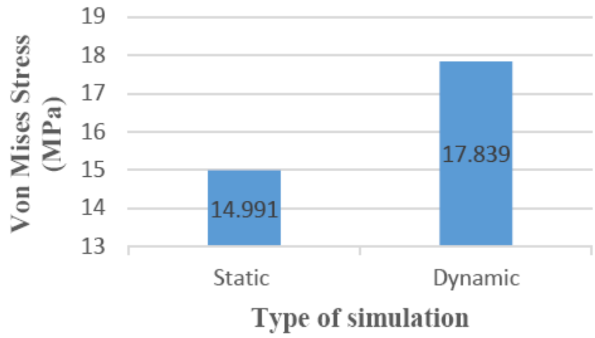


Figure 6. Von Mises stress for the static and dynamic simulation.

Table 2. Maximum deflections, strains, and stresses (components and principals) that generated in the sockets for the two types of simulation.

Simulation type	U_x (mm)	U_y (mm)	U_z (mm)	$\varepsilon_x(\mu\varepsilon)$	$\varepsilon_y(\mu\varepsilon)$	$\varepsilon_z(\mu\varepsilon)$
Static	0.089	0.015	0.174	-301.3	-330.7	-397.3
Dynamic	-0.104	-0.018	-0.197	388.6	312.2	312.6
Soket	S_x (Mpa)	S_y (Mpa)	S_z (Mpa)	S_1 (Mpa)	S_2 (Mpa)	S_3 (Mpa)
Static	-11.102	-11.335	-12.725	11.201	-3.897	-15.196
Dynamic	16.725	12.746	11.849	18.882	-5.230	-18.623

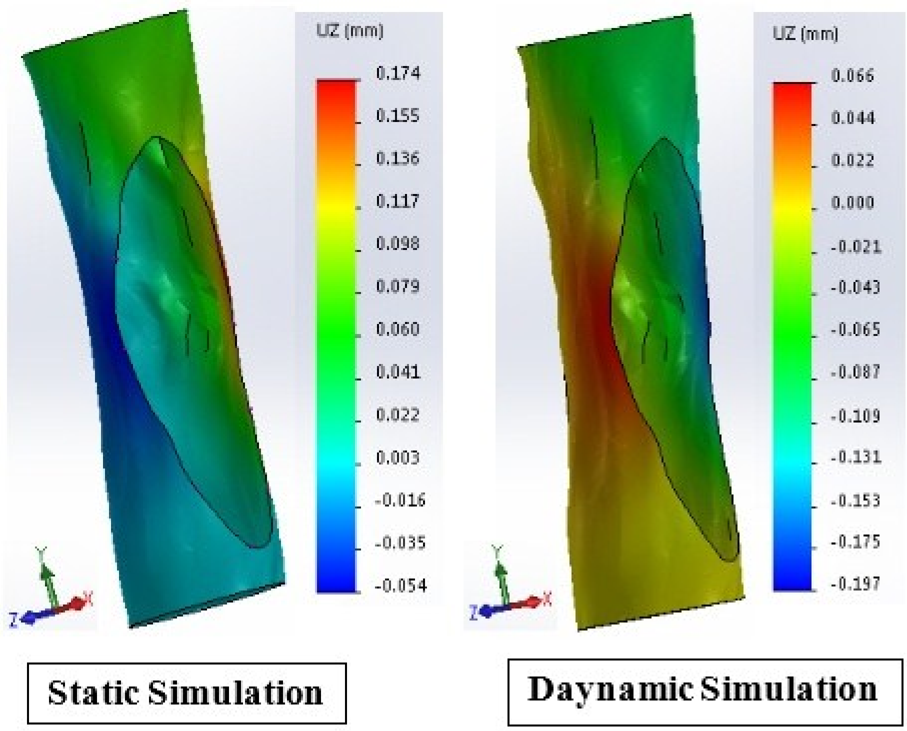


Figure 7. Contour plots of the maximum deformation for the two types of simulation.

A dynamic load can have a great effect than a static load of the same magnitude because of the structure inability to respond quickly to the loading (by deflecting). The increase in the effect of a dynamic load is given by the dynamic load factor (DLF), which is found by dividing the Von Mises stress that resulted from the dynamic solution to the Von Mises stress that resulted from the static solution.In this case, the DLF was found equal to 1.2.

5.2.2 Simulation using mathematical equation

In this type of simulation, the maximum load was applied in the two sockets which resulted from the mathematical equation and equal to 117 Kpa. To know the difference between the effect of the dynamic simulation with applying the experimental result from the F-socket device, and with applying the result from the analytical equation, Table 3 shows a comparison between the results of the two methods. Figure 8 shows the difference in the Von Mises as contour plot for the two type of simulation.

Table 3. Maximum deflections, strains, and stresses (components and principals) that generated from the experimental and analytical load in the new sockets.

	U_x (mm)	U_y (mm)	U_z (mm)	$\varepsilon_x(\mu\varepsilon)$	$\varepsilon_y(\mu\varepsilon)$	$\varepsilon_z(\mu\varepsilon)$
Experimentally	-0.104	-0.018	-0.197	388.6	312.2	312.6
Analytically	-0.124	-0.022	-0.225	-242.8	422.2	435.9
	S_x (Mpa)	S_y (Mpa)	S_z (Mpa)	S_1 (Mpa)	S_2 (Mpa)	S_3 (Mpa)
Experimentally	16.725	12.746	11.849	18.882	-5.230	-18.623
Analytically	2.718	14.688	13.109	18.318	3.872	-7.215

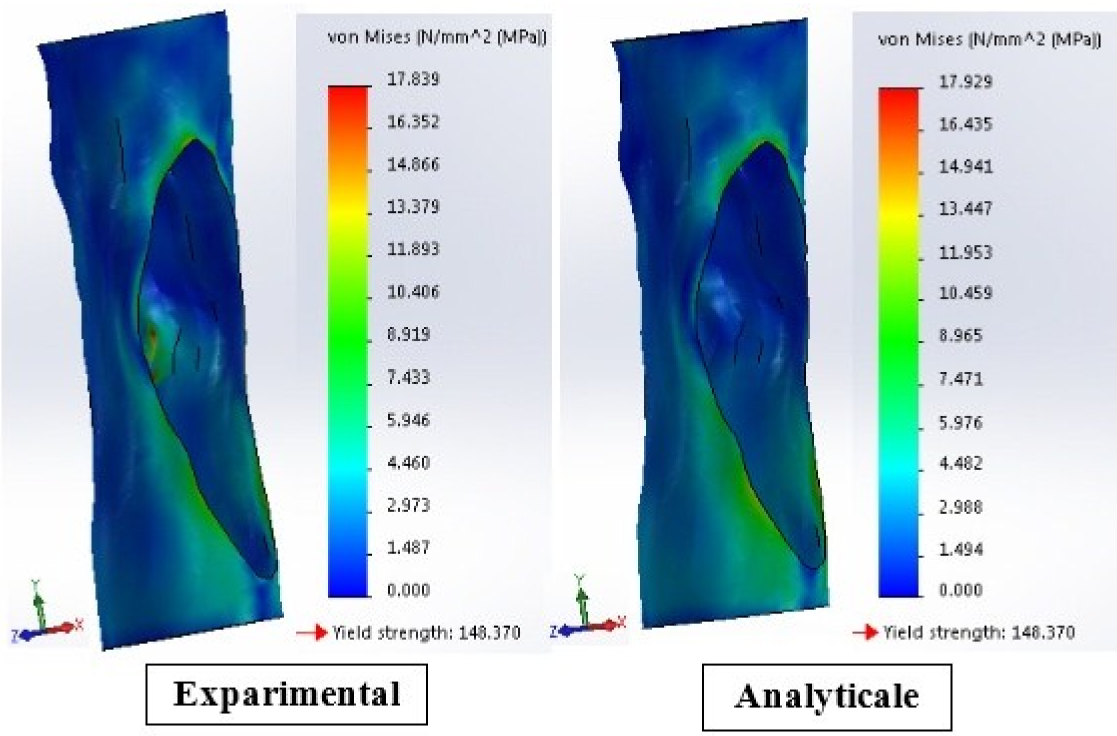


Figure 8. The difference in the Von Mises as contour plot for the two type of simulation.

6. Conclusions

In this study, the following conclusions are drawn,

1. The Stump-Socket load distribution by using the mathematical equation has an acceptable difference as compared to that from an F-Socket device which is 27.7%, so it is possible to depend on the analytical expressions only and dispense on the F-Socket device in the necessary occasions in cases of the unavailability of the F-socket.
2. The amount of the DLF found to be 1.2, which is considered as a logical value that refers to acceptable simulation results.

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References

[1] A. Ogawa, G. Obinata, Member, IEEE, K. Hase, A. Dutta, and M. Nakagawa, "Design of Lower Limb Prosthesis with Contact Pressure Adjustment by MR Fluid," 30th Annual International IEEE EMBS Conference, pp. 20-24, 2008.

[2] F. Appoldt, L. bennett, and R. contini, "Stump-Socket Pressure in Lower Extremity Prostheses," Biomechanics, Vol. 1, pp. 247–257, 1968.

[3] X. Jia, M. Zhang, and W. C.C Lee, "Load Transfer Mechanics between Transtibial Prosthetic Socket and Residual Limb - Dynamic Effects," Biomechanics, Vol. 37, pp. 1371–1377, 2004.

[4] S. Ali, N. A. A. Osman, N. Mortaza, A. Eshraghi, H.Gholizadeh , and W. A. B. B. W. Abas, "Clinical Investigation of the Interface Pressure in the Trans-Tibial Socket with Dermo and Seal-In X5 Liner During Walking and Their Effect on Patient Satisfaction," Clinical Biomechanics, Vol. 27, pp. 943-948, 2012.

[5] G. Colombo, C.Comotti, D.F.Redaelli, D.Regazzoni, C.Rizzi, and A.Vitali, "A Method to Improve Prosthesis LEG Design Based on Pressure Analysis at the Socket-Residual Limb Interface," Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2016.

[6] M. Tanaka, Y. Akazawa, A. Nakagawa, and I. Kitayama, "Identification of Pressure Distribution at the Socket Interface of an Above-Knee Prosthesis," Elsevier, pp. 379-384, 1997.

[7] M. Naeff, and T. V. Pijkeren "Dynamic Pressure Measurements at the Interface between Residual Limb and Socket - the Relationship between Pressure Distribution, Comfort, and Brim Shap," Bulletin of Prosthetics Research BPR, Vol. 17, No. 1, pp. 35-50, 1980.

[8] M. J. Jweeg, A. A. Alhumandy, and H.A. Hamzah, "Material Characterization and Stress Analysis of Openings in Syme's Prosthetics," International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, Vol.17, No. 04, pp. 100-108, 2017.

[9] A.A. Alhumdany, M. AL- Waily, and M.H. Khadim, "Experimental Investigation for Powder Reinforcement Effect on Mechanical Properties and natural Frequency for Isotropic Hyper Composite Plate with Variable Boundary Conditions," International Journal of Energy and Environment Foundation (IEEF), Vol. 5, Issue 5, pages 499, 2016.

[10] M. Zhang, A.R. Turner-Smith, V.C. Roberts, and A. Tanner, "Frictional Action at Lower Limb/Prosthetic Socket Interface," Elsevier, Vol. 18, No. 3, pp. 207-214, 1996.