International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Parametric Analysis to Investigate the Stiffness to Weight Ratio of Syme's Socket

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Received 01 Nov 2017, Accepted 01 Jan 2018, Available online 04 Jan 2018, **Vol.8, No.1 (Jan/Feb 2018)**

Abstract

A finite element model of Syme's socket was built to investigate the influences of parameters alterations on the weight of socket and stiffness to weight ratio under general loading. For the prosthetic studies, it is known that the weight of the socket is one of the important features to consider during the assessment of the Syme's prosthesis. To achieve this aim, four materials have been used in the parametric analysis by SOLIDWORKS® program; these materials were the proposed laminate, Polypropylene (PP), Polylactic acid (PLA) and Acrylonitrile butadiene styrene (ABS) with varying the socket thickness for the last three materials. The obtained results proved the effectiveness of the proposed material among the four materials with regard to stiffness to weight ratio in despite of the change of thickness for the other materials.

Keywords: *Parametric study, stiffness to weight ratio, Syme's socket*

1. Introduction

The weight is considered as one of the most important characteristics that must take into consideration in prosthetics, one among many factors during the evaluation of prosthetic socket. It minimizes the muscular effort required during locomotion so, as the weight of the prosthesis increases, more energy will need to move it through space. In general, unilateral transtibial amputees need (20-25%) more energy cost and locomotion slower when utilizing a prosthesis than healthy persons (Gailey, 1994). Energy consumption Chan S, 2003)whereas, without a prosthesis, transtibial, transfemoral and partial foot amputees consumed more energy than Syme's amputees (chmalz T, Blumentritt S, 2002). Most of the prostheses are much lighter than anatomical limbs, which they have replaced.

The weight of any transtibial prosthesis does not exceed more than 2 Kg whereas the weight of lost limb for a transtibial amputee who weights seventy during locomotion with a transtibial prosthesis is lower by (3-5%) than Syme's prosthesis (Lin-kilograms is closer to (4 Kg) (Dempster, 1955) in contrast Syme's amputee, therefore, the weight of Syme's prosthesis is an important factor to minimize the consumption energy thus comfort of the amputee. There are three different types of stresses in Syme's socket; compression stress resulting from direct thrust load, bending stress resulting from a tendency for the socket to bow laterally and bending stress resulting from a tendency for the socket to bow posteriorly. The eccentricity of the applied load resulted in these bending stresses (Radcliffe, 1961), hence the importance of stiffness appeared to resist the compression loads and moments that generated during locomotion of the amputee.

The axial and flexural stiffness can be improved by increasing the moment of inertia of the socket by increasing the wall thickness of the socket consequently increasing the weight of the socket.

The stiffness-to-weight ratio is a measure of the influences of the efforts of weight reduction on the prosthesis stiffness.

Barbara and Dudley conducted an investigation to know the effect of the stiffness of both materials the socket and the liner on the interface pressure. They found out that the increasing the stiffness of the socket resulted in increased the interface pressure on tibia crest and tibial flare whereas the pressure on the patellar tendon and fibular end decreased. In contrast, the increasing the stiffness of the liner resulted in decreased the pressure on the medial tibial plateau and the posterior popliteal regions.

M.J. Jweeg and Bakr investigated the influence of increasing the thickness of Syme's socket that manufactured from polypropylene on the stiffness to weight ratio. They found that whenever the thickness of the material has increased, the stiffness to weight ratio would increase. They concluded that the stiffness

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DOI: https://doi.org/10.14741/ijcet.v8i01.10885

to weight ratio in the socket with a posterior cutout is higher than its in the socket with medial cutout.

Paolo and Alena experimentally measured the axial and torsional stiffness for different types of pediatric prosthetic feet (Trulife Child's Play, Kingsley K07J Juvenile Symes, TRS little and College Park Truper) during heel loading, mid foot loading, forefoot loading, Dorsiflexion and Plantarflexion. They concluded that the axial stiffness of TRS prosthetic foot is better than other types of prosthetic feet where the stiffness increased with increasing the feet size. In addition, they observed that the torsional stiffness of Truper prosthetic foot is less than other types.

2. Finite Element Method

Finite element method is a numerical method attempting to find an approximated solution of the distribution of the field variables in the problem domain which is difficult to get theoretically where it is done by dividing the problem domain in to different elements and applies known physical laws to any small element, each of which ordinarily has a very simple geometry (Liu,, 2013).

In recent years, thousands of engineering problems have been solved effectively using software packages. The software packages such as ANSYS, SOLIDWORKS, NASTRAN, ABAQUS etc. have been constructed depended on the finite element analysis technique as a powerful tool to obtain a solution for complicated problems where analytical solutions cannot be applied. In this work, SOLIDWORKS® software was used to solve Syme's socket model under loading. In general, the proceedings of computational modelling utilizing the FEM largely include four stages:

- Model shape generation.
- Mesh density
- Material properties.
- Boundary conditions.

1.1 Model of Syme's socket

Model of the Syme's prosthetic socket has built to study the influences of parameter variations on the stiffness to weight ratio under general loading.

This model depended on the geometric of the manufactured prosthetic socket. It is known that the prosthetic socket has a complex geometry; therefore, it is difficult to get an accurate geometry that has the same dimensions, which the socket had.

The portable laser 3D scan700 from CREAFORM has been used to build the modelling of the socket. The scanning of modelling includes the following steps as shown in **Fig.2**.

- Set up, plug in the portable laser 3D scan700, and connected to a laptop (VX elements software).
- Apply positioning targets (circular stickers placed on or off a part used to create a 3D reference for the scanner to position itself. These stickers can be placed anywhere depending on the part complexity. The scanner has to see a minimum three targets to create a proper reference frame).
- Scan the socket.
- Create an editable mesh and export with mesh STL file.

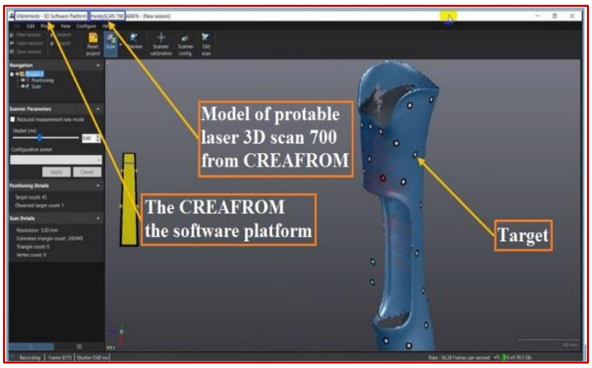

Figure 1: Software windows of VX-elements

The final geometry of scanned socket includes some of the bad features so; it must eliminate in addition to the need to align the meshed socket to the origin. Geomagic Studio 2014 is the famous reverse engineering software that is offered by American Geomagic cooperation where the functions of this program are aligned the meshed socket to the origin, remove isolated patches, fill holes, specify the upper, bottom and cutout contour and improve the mesh (smooth mesh, trimming of undesired mesh).

The geometry of the Syme's prosthetic socket resulted from Geomagic studio program is a surface body, which may envelop an entire geometric shape of a target mesh.

The geometry of socket has imported as (STL or IGES) files to SOLIDWORKS® software.

1.2 Appropriate mesh density

Finite Element division or Meshing is the process utilized to fill the surface model with nodes and elements, that is, to build the FEA model. Mesh generation is a very important task where it can be a very time-consuming task to the analyst, and usually, an experienced analyst will produce a more credible mesh for a complex problem, unfortunately, there is no definite procedure for getting optimum mesh density to give reasonably good results.

Mesh density is considerably important. If the mesh is very coarse, the outcomes can include critical errors. If the mesh is so fine, it will squander computer resources, take excessively long run time. The domain has to have meshed properly into elements of specific shapes such as triangles and tetrahedral.

The SOLIDWORKS® software automatically creates a shell mesh for surface geometries with uniform thickness. A shell element created at the mid-surface with the nodes.

It has six degrees of freedom of each node translation in the nodal x, y and z-directions and rotation about x, y and z-axes where the shells are triangular with three vertex nodes or three vertex and three mid-edge nodes as shown in **Fig.2.**In the SOLIDWORKS®, there are three mesh options; standard, curvature-based and blended curvature-based mesh where the curvature based mesh is adopted in the solution.

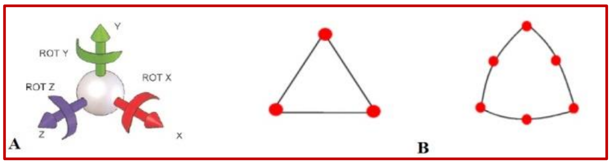

Figure 2: shell element

A. Degrees of freedom for shells B.SW Simulation shell

Mechanical Properties of the Used Materials

In this work, four different materials have been used to determine the best materials suitable with regard to the weight and the stiffness-to-weight ratio of Syme's socket.

These materials are the proposed laminate, Polypropylene (PP), Polylactic acid (PLA) and Acrylonitrile butadiene styrene (ABS). The proposed laminate consists of 4-layers of carbon fibers and 6-layers of perlon fibers as reinforced materials and acrylic resin as a matrix. The core of laminate has reinforced with two layers of carbon fibers in addition to reinforcing the skin with one layer of carbon fibers for both upper and lower skin. Polypropylene is an economical material offers a combination of outstanding physical, chemical, mechanical, thermal and electrical properties not found in any other thermoplastic. It has low impact strength, but its tensile strength is good in addition to its lightweight (M.J. Jweeg, 2008). Polylactic acid (PLA) and Acrylonitrile butadiene styrene (ABS) are filaments that utilized in the manufacturing of prosthetics by using 3D printer method where PLA filaments are a biodegradable thermoplastic polyester derived from renewable resources and it is the most used and it is Eco-friendly material. Both of these filaments have excellent mechanical properties. The mechanical properties for (PLA) and (ABS) that have taken from the manufacturer (Ultimaker, 2017) in addition to the mechanical properties for both of polypropylene (Radi, 2008)and the proposed laminate are as shown in **Table 1**.

Table 1: Mechanical and physical properties of (PLA), (ABS) and (PP)

Material	σ_{ult} (MPa)	σ_y (MPa)	E (GPa)	ν	ρ (g/cm^3)
PLA		49.5	2.346	0.36	1.24
ABS	41	39	1.68	0.35	1.1
PP	32	25	1.235	0.33	0.9
Laminate	153.43		4.675	0.34	1.235

2. Boundary conditions

The boundary conditions play a crucial role in resolving the simulation. The main objective of a finite element analysis is to know how a model or a component complies with certain loading conditions. The word loads in SOLIDWORKS® terminology includes boundary conditions and externally or internally applied force functions, for example, displacement, forces, pressures, temperature and gravity in structural disciplines. Loads divided into six categories: boundary condition, forces (concentrated load), surface load, body loads, inertia loads and coupled field loads.

In this work, Syme's socket model, (the lowest part of it), was spatially constrained (All DOF restrained that means all of its six degrees of freedom; U_x, U_y, U_z, Rot_x, Rot_y, Rot_z are set to equal zero). Three unit loads are severally applied on the Syme's socket; axial load F_y, bending load F_z and twisting torque M_y with varying the socket thickness from 3-5 mm for PP, PLA and ABS, but used the thickness of proposed laminate (3mm) that has been obtained by the manufacturing process for this laminate. The program was performed and the deflections under these unit loads were obtained.

3. Parametric Analysis

Parametric analysis of the model may be utilized to give insight into Syme's socket where such analyses cannot conduct only feasible using numerical methods. Analyses have conducted for an amputee with Syme's amputation who weights (76 Kg).

In SOLIDWORKS®, there is an option called design study that was used for obtaining the more effective material. There are three main points that must be defined in design study which are:

- Define the variables by using simulation parameters.
- Define the limitations.
- Define the goals by using sensors.

In the prosthetic and orthotics field, each designer's goal is to obtain a lightweight and comfortable prosthesis, but within specific limitations and according to these variables, limitations and goals, the parametric study will choose the best material among multiple scenarios with regard to the weight and stiffness to weight ratio.

The constraints, which are specified in this parametric study, include; the equivalent stress must be less than yield stress. The lightweight and high stiffness-to-weight ratio of Syme's prosthesis are the main goals that wish to investigate in this parametric analysis.

4. Results and Discussion

4.1 The lightweight material

Table 2 gives results of weights of the four materials, which have obtained by parametric analysis. The thickness of prosthetic socket, which was manufactured of polypropylene, PLA and ABS depends on the weight of patient and his activity level whether inactive or active (heavy-duty or super-duty), in contrast the proposed laminate whose thickness depends on the type and number of used layers of fibers and according to the activity level of a patient. An empirical formula is used to determine the required thickness (Colombo,, 2013)

$$\text{Socket thickness (mm)} = \frac{\text{Patient weight (Kg)}}{20}$$

According to the above-mentioned formula and based on the mass of the amputee, the thickness of the socket must be equal to or more than 4 mm in case of using polypropylene, PLA and ABS. It has found that the weight of both the proposed material and polypropylene is close.

Table 2: Results of the weights of four used materials

Material	Thickness (mm)	Weight (N)
Proposed laminate	3	3.87
PP	3	2.82
	4	3.76
	5	4.71
PLA	3	3.89
	4	5.19
	5	6.49
ABS	3	3.45
	4	4.6
	5	5.75

4.2 Stiffness to weight ratio

Table 3, Table 4 and **Table 5** show the results of stiffness to weight ratio under unit loads of F_y= -1 N, F_z =1 N and M_y= 1 N.m calculated for the model of the prosthetic socket at different socket thicknesses, ranged from 3mm to 5mm for PP, PLA and ABS in addition to using 3mm socket thickness for the proposed laminate. Axial, bending and torsion stiffness were calculated by dividing the unit load to the maximum deflection that has obtained by parametric study. The minimum deflection is the maximum stiffness under the same load where **Fig.3** gives the values of deflection under unit loads for proposed laminate.

Table 3: Axial stiffness to weight ratio

Material	Thickness (mm)	Maximum deflection (mm)	Axial stiffness (N/mm)	Stiffness to weight ratio (N/mm.N)
Laminate	3	-0.00269	371.74	95.83
PP	3	-0.01021	97.94	43.64
	4	-0.006681	149.67	39.71
	5	-0.004914	203.5	34.19
PLA	3	-0.005366	186.35	47.85
	4	-0.003514	284.5	54.8
	5	-0.002585	386.8	59.6
ABS	3	-0.007497	133.38	38.6
	4	-0.004116	242.9	52.7
	5	-0.00303	330	57.3

Table 5: Bending stiffness to weight ratio

Material	Thickness (mm)	Maximum deflection (mm)	Bending stiffness (N/mm)	Stiffness to weight ratio (N/mm.N)
laminate	3	0.0547	18.28	4.71
Polypropylene	3	0.2073	4.82	1.706
	4	0.144	6.94	1.84
	5	0.1086	9.208	1.95
PLA	3	0.1092	9.15	2.35
	4	0.07582	13.18	2.539
	5	0.05719	17.48	2.69
ABS	3	0.1525	6.55	1.89
	4	0.1059	9.44	2.049
	5	0.0785	12.5	2.17

Table 4: Torsion stiffness to weight ratio

Material	Thickness (mm)	Maximum deflection (Deg)	Torsion stiffness (N.m/Deg)	Stiffness to weight ratio (N.m/Deg.N)
laminate	3	0.586	1.706	0.44
PP	3	2.218	0.45	0.159
	4	1.184	0.844	0.224
	5	0.7226	1.38	0.293
PLA	3	1.173	0.85	0.218
	4	0.6274	1.59	0.306
	5	0.3836	2.6	0.401
ABS	3	1.635	0.61	0.177
	4	0.8742	1.14	0.248
	5	0.5342	1.87	0.325

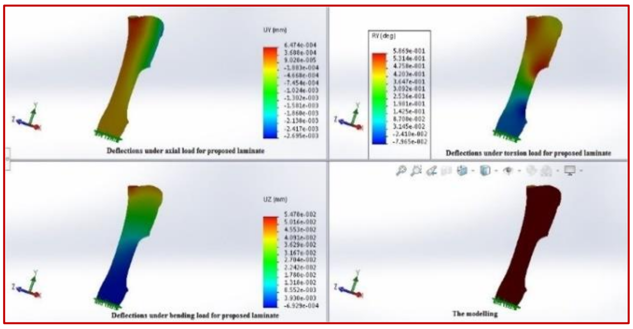

Figure 3: Results of maximum deflection under different unit loads for proposed laminate

The above-mentioned results indicate that the proposed laminate was the best material, among four materials used in this study with regard to axial stiffness to weight ratio, bending stiffness to weight ratio and torsion stiffness to weight ratio. It observed that the axial stiffness for all used four materials is higher than bending and torsion stiffness. It is known that each of stiffness is directly proportional to Young's modulus and according to the following relationships:

K_{axial} α E ×A
$K_{bending}$ α E ×I
$K_{torsion}$ α G ×J
where $G = \frac{E}{2(1+v)}$

Because of the shear modulus (G) is equal to about half of Young's modulus, therefore, its value is always less than the values of bending and axial stiffness.

Conclusions

In this study, it has concluded that the polypropylene has the lowest value in the stiffness-to-weight ratio in spite of changing the thickness of socket from 3-5 mm while the proposed laminate is the best material, among four materials with regard to the weight and stiffness to weight ratio.

Nomenclature

U_x: Displacement in direction x-axis in (mm).
U_y: Displacement in direction Y-axis in (mm).
U_Z: Displacement in direction Z-axis in (mm).
Rot_x: Nodal rotation about X-axis in degree
Rot_y:Nodal rotation about Y-axis in degree
Rot_Z:Nodal rotation about Z-axis in degree

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