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Stress Distributions of Lower Limb Prosthetic Socket *

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Abstract

The aim of this work is to determine the stress patterns of a prosthetic socket. This allows the socket geometry to be more accurately modeled. The analyzed socket is a medium length lower left leg.

The pressure values between the stump and the socket are taken from published data. While the loading on the socket base is evaluated theoretically. Three types of sockets, PP (5mm), PP (3mm) and a standard laminate (3mm) have used in this work.

The results showed that the stresses produced in the socket frame are low comparing with the yielded stresses of the materials. The PP (5mm) and the laminated socket show deformations below the critical value (i.e. 2mm), while the PP (3mm) gave a deformation of (2.9mm) which is higher than the critical value.

الخلاصـــــة

الهدف من البحث هو ايجاد مسار الأجهادات للوقب للتمكن من تمثيل الشكل الهندسي للوقب بدقة. الوقب المستخدم هو الطرف السفلي ذو الطول المتوسط.

أخذت قيم الضغوط من احدى البحوث المتعلقة بالموضوع وتم حساب القوى المؤثرة على قاعدة الوقب نظريا. درست ثلاثة انواع من الوقب ، وهي البولي بروبلين بسمك ٥ ملم وسمك ٣ ملم أما النوع الثالث فهو عبارة عن مادة مركبة بسمك ٣ ملم.

بينت النتائج أن الأجهادات المتولدة في الوقب أقل من اجهاد الخضوع للمادة البولي بروبلين بسمك ٥ ملم والمادة المركبة عانت تشوه أقل من القيمة الحرجة (٢ ملم) بينما البولي بروبلين يسمك ٣ ملم فقد عانى تشوه مقداره ٢,٩ ملم.

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Introduction

Amputation of a lower limb is most commonly performed due to trauma, disease of the limb and severe accident. The two most often performed amputation procedures are truncation of the femor bone (Above the Knee -AK-) and truncation of the tibia bone (Below the Knee -BK-) [1].

Physical loss of the anatomy of the lower limb results in loss of gait function. In BK amputees this loss is due partly to the loss of the articulated ankle joint, the loss of the joints of the foot (including the metatarsal-phalangeal joints), and the loss of the muscles of the anterior and posterior compartments of the shank. The purpose of a below knee leg prosthesis is to replace the function lost due to the physical loss of anatomy.

Below knee prostheses are typically comprised of four major components, as shown in **Fig.(1)**.

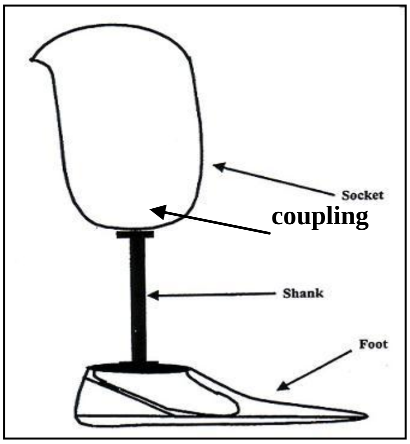


Figure (1) The prosthesis components [1]

Most researchers concentrated their investigations on the contact pressure values between the stump and the prosthetic socket otherwise the stresses distribution of the prosthetic socket. Appoldt and Bennett [2], found the loading on an above-knee fiberglass socket by building the socket with the pressure transducers incorporated. Unfortunately their results are only accurate for the single socket used in the experiment. This is due to all modern sockets having different geometries and external loads due to differences in the amputees. Bielefeldt and Schreck [3], investigated the difference in loading of four different material sockets, during stance phase, for the same patient. Their sockets were built with transducers incorporated. Ross Stewart [4], developed finite element model for above-knee prosthetic socket using PAL2 program. The external forces were found for the prosthetic leg, while the characteristics for the socket loading were assumed. Fiberglass and polypropylene sockets were used in this analysis. Ming Zhang [5], developed a finite element model based on the three dimensional geometry of the residual limb and the internal bone structure of a below-knee amputees. The shape of the residual limb was obtained from a digitizer. The contact between the residual limb and the socket was introduced in the model analysis. The aim of the present work is to shed some light on the following points:

1. The pressure distribution between the stump and the socket.
2. Asymmetry in socket shape.
3. Design of the socket and behavior of its materials.
4. Considering the pressure relief regions of the socket in its design.
5. The shock absorbing phenomenon of prosthetic feet at heel strike for many types of feet.

2. Phases of Gait

The motion of walking is divided into two phases for each step. These are the stance phase and the swing phase. The stance phase takes approximately 63% of the total time of the step. This value varies for each subject. Stance phase starts with heel contact while the swing time starts after lifting the foot and shank. **Figure (2)** shows the gait phases [4].

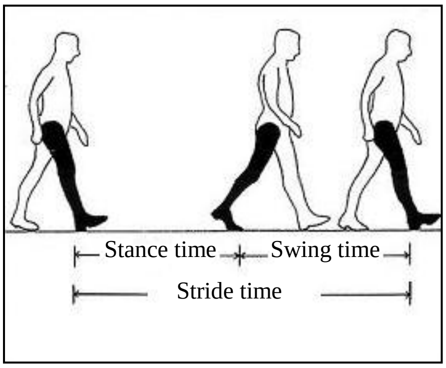


Figure (2) Gait phases [4]

3. Ground Reaction forces (GRFs)

The ground reaction force is the main force acting on the body during walking. It consists of a vertical component and two horizontal components (Rx, Ry, Rz). **Figure (3)** shows the components of ground reaction forces.

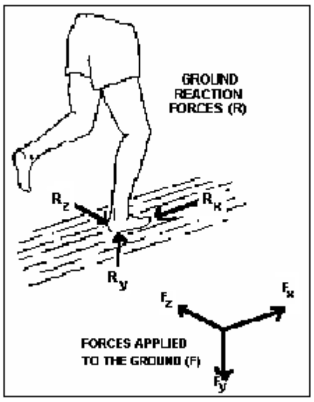


Figure (3) GRFs [5]

These forces are found by having a subject walking across a force plate in the form of a walking. A force plate is an instrument which provides readings of the forces and moments applied to its top surface while the foot of the subject is in contact with the plate.

Data of GRFs are readily available. These are usually in the form of percentage of the body weight versus phases of gait. The lateral component has been neglected as it is insignificant compared with the vertical force [5]. The used values of vertical force as a percentage of the body weight for heel strike, mid-stance and push-off are 130, 70 and 110% respectively while the used values of horizontal force for the three phases 20, 4 and 15% respectively.

4. Procedure

When the socket is loaded by the stumps normally, the load would have transferred nonuniformally. This is due to parts of the stump carrying higher load than other parts of the stump. Parts of the stump such as bones and tendons can support more loads than skin and muscles. During gait, the load transfer distribution also varies. There is no definite pressure distribution between the socket and the stump.

The PTB (Patellar Tendon Bearing) socket used locally, analysis the design criterion which states that load increases on the patellar ligament with minimum contact pressure placed over the sensitive areas.

Interfacial pressure measurements require a proper measurement technique, including the use of transducers and their placements at the prosthetic interface. The experimental data of pressure distribution at the residual limb and socket interface are taken from reference [6]. **Figure (4)** shows the location of pressure measurement sites used in reference [6]. The testing procedure included four subjects wearing PTB sockets. Each subject was required to walk with the prosthesis for at least 15 minutes to become accustomed to the test socket. The tests were divided into static (standing) and dynamic (walking) stages.

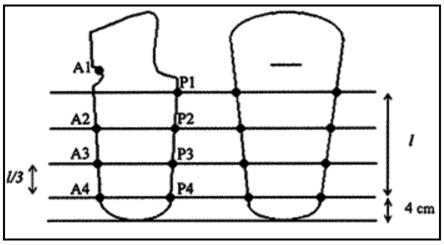


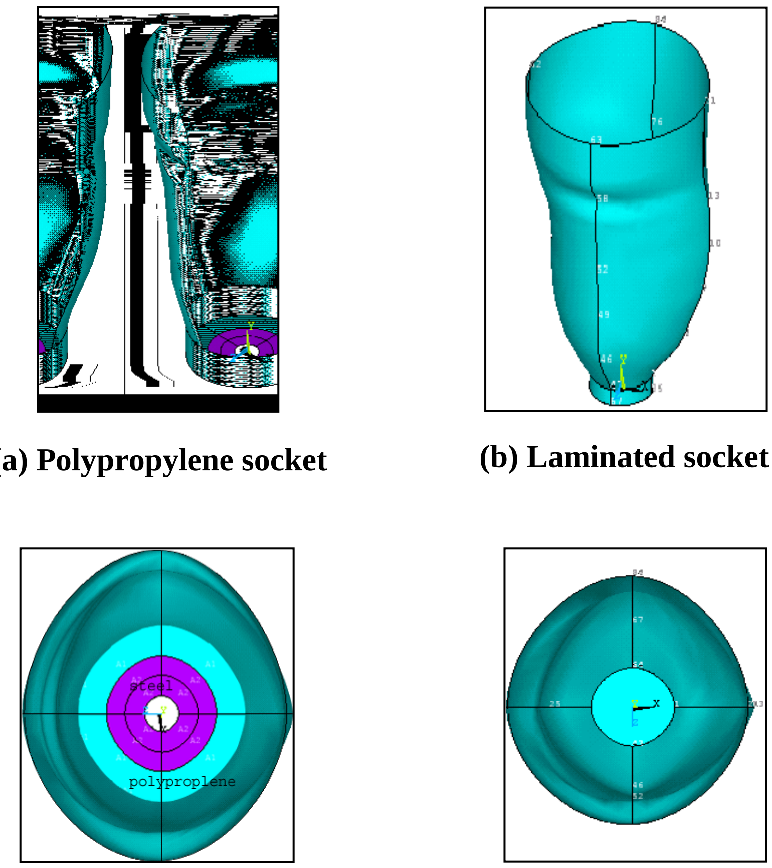
Figure (4) Pressure transducer locations

The average value of l is 88mm of four subjects having (60,80,98 and 113mm).

5. Numerical Analysis for the Socket Stress Distribution

5-1 Finite Element Model

The prosthetic socket is not a simple shape to be modeled with finite element. Due to its unique geometry, no simplification of the shape or symmetrical shape is possible. **Figure (5)** shows the models.



(a) Polypropylene socket **(b) Laminated socket**

(c) Top view **(d) Top view**

Figure (5) Models of prosthetic socket for the finite element analysis

5-2 Material Properties

The prosthetic socket may be manufactured from polypropylene (thermoplastic material) or composite materials (laminates).

The sockets used in the analysis are polypropylene socket and laminate socket (2-layers perlon, 6-layers fiberglass and 2-layers perlon) with orthocryl resin. The mechanical properties of polypropylene are measured experimentally. While the mechanical properties of the laminate socket are taken from reference [4].

Table (1) shows the material properties of polypropylene and the laminate.

Table (1) Material mechanical properties

Material	Young's Modulus(MPa)	Yield Strength or Tensile Strength (MPa)	Poisson´s Ratio
Polypropylene	1235	25 (Yield Strength)	0.33
Laminate	3100 [4]	68×(Tensile Strength)	0.28 [4]
Steel	200000 [7]	520 [7]	0.3 [7]

5-3 Element Type

For polypropylene, the element types used is SHELL63. For laminated socket, SHELL 63 is used for socket frame. The bottom base of the laminated socket consists of a solid cylinder of 20 mm radius and 20 mm height. SOLID 92 elements are chosen to mesh the volume of solid cylinder. Surface area boundary lines are divided evenly to allow the production of a consistence mesh through the socket.

5-4 Loading

Tables (2), **(3)** and **(4)** show the average values of pressure between the socket and the stump at heel strike, mid-stance and push-off respectively **[6]**. From the results of pressure values for the four subjects, it is possible to conclude that there was no definite relationship between the pressure values and the socket height. Therefore, the averaged pressure values at each transducer for the four subjects would be used in the FE model. In effect, every person has his particular pressure distribution because there are factors which affect this distribution such as, shape of the stump, alignment and thigh muscle strength. The averaged body weight is 75.5 kg for body weights of four subjects (76.2, 75.4, 87 and 62.8 kg). The pressures distribution between each transducer is assumed linear. The pressure applied to the socket is as the pressure on area of definite length with of (1mm). The effect of GRFs on the socket will be explained in the next article.

Table (2) The average pressure values in (kPa) at heel strike

Level	Anterior	Posterior	Medial	Lateral
A4-P4	25.87	40.73	24.9	51.68
A3-P3	6.8	49.7	22.03	49.15
A2-P2	5.75	52	30.03	56.15
P1	-	35.2	60.4	26.08
A1	8.2	-	-	-

Table (3) The average pressure values in (kPa) at mid-stance

Level	Anterior	Posterior	Medial	Lateral
A4-P4	24.3	26.98	19.2	45.67
A3-P3	5.3	36.9	20.83	35.93
A2-P2	4.55	34.68	29.93	31.58
P1	-	31.83	60	19.53
A1	1.98	-	-	-

Table (4) The average pressure values in (kPa) at push-off

Level	Anterior	Posterior	Medial	Lateral
A4-P4	9.4	38.38	26.1	32.35
A3-P3	5.03	43.8	26.1	39.28
A2-P2	4.85	44.68	37.28	32.73
P1	-	37.85	67.63	21.37
A1	49.73	-	-	-

6. The Effect of GREs on the Socket

The polypropylene socket base is different from the laminated socket, as shown in **Fig.(5)**. For laminated socket, a cross section at a distance 20 mm from the base is taken. Therefore, the boundary conditions for the laminated socket base are built in. For polypropylene socket, the inner steel ring at the base is built in, because of the bolt passing through it, while the outer ring of the base is under pressure produced by GRFs.

6-1 Pressures produced by GRFs at heel strike for polypropylene socket

From available data, the vertical and horizontal forces of ground reaction forces at heel contact are:

$$\mathbf{Fy = (1.3)\ (75.5)\ (9.81) = 926.851\ N \quad \ldots\ldots (1)}$$

$$\mathbf{Fx = -(0.2)\ (75.5)\ (9.81) = -148.131\ N \quad \ldots\ldots (2)}$$

The maxim angle at heel strike is 30° [7], assuming that the length of the shank is 250mm. **Figure (6)** shows the geometry of the foot-shank and the location of GRFs.

The force components are transferred to the socket base as a vertical load and a moment about the center of the socket base. The horizontal force affects the bolt mainly which fastens the socket to the shank.

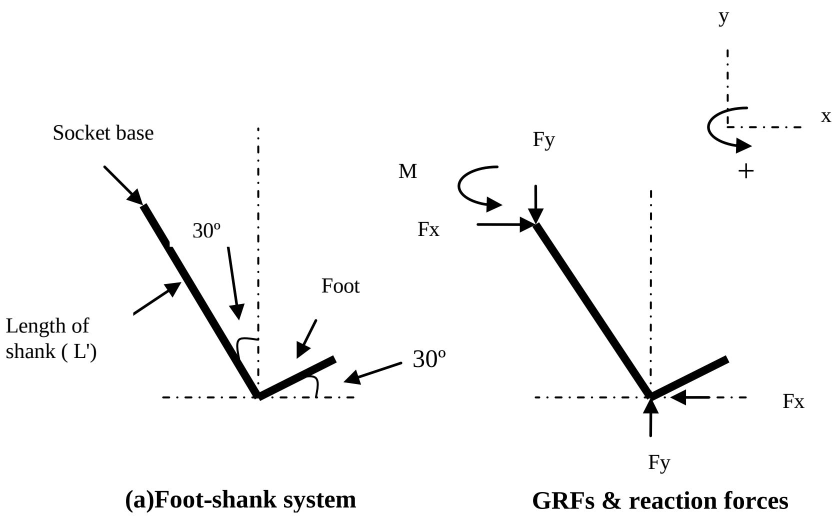


Figure (6) The foot-shank system at heel-strike [8]

The moment at the end of the shank is:

$$+\ \Sigma M = Fx\ (L'\cos 30^{o}) + Fy\ (L'\sin 30^{o}) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

This moment is applied to the socket base as a distributed pressure along the base area. From Equation (3), the (ΣM=-83785.072 N.mm).

At the end of the shank, the resultant force which is parallel to the shank produced by Fx and Fy is:

$$Fy' = Fy\cos 30 + Fx \sin 60$$
$$= (962.851)\ (\cos 30^{o}) + (148.131)\ (\sin 30^{o})$$
$$= 907.918 \text{ N}$$

$$PFy' = (Fy')\ (4) / \pi(Do^2\text{-}Di^2)$$
$$= (907.918)\ (4)/\pi(702\text{-}302) = 0.288 \text{ N/mm}^2$$

6-2 Pressures produced by GRFs at mid-stance for polypropylene socket

From available data, the vertical and horizontal forces of ground reaction forces at mid-stance phase are:

$$Fy = 0.7\ (75.5)\ (9.81) = 518.458 \text{ N}$$

$$Fx = -0.04(75.5)\ (9.81) = 29.626 \text{ N}$$

From **Fig.(7)**,

$$+\ \Sigma M = 29.626\ (250) - 518.458(60)$$
$$= -23700.98 \text{ N.mm}$$

$PFy = Fy\ (4) / \pi\ (Do^2\text{-}Di^2)$

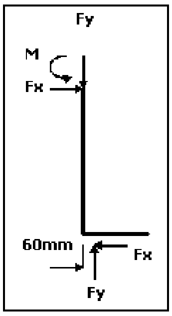


Figure (7) GRFs and reaction forces at mid-stance [8]

6-3 Pressures produced by GRFs at push–off for polypropylene socket

From available data, the vertical and horizontal forces of ground reaction forces at push-off phase are:

$Fy = (1.1)\ (75.5)\ (9.81) = 814.72\ N$

$Fx = (0.15)\ (75.5)\ (9.81) = 111.098\ N$

From **Fig.(8)** the induced forces along x' and y' axes are:

$Fy' = (814.72)\ (\cos 70^o) + (111.098)\ (\sin 70^o) = 383.048\ N$

$Fx' = (814.72)\ (\sin 70^o)\text{-}(111.098)\ (\cos 70^o) = 727.588\ N$

$+\ \Sigma M + 383.048(250)\text{-}(727.588)\ (250) = 0$

$\Sigma M = \text{-}86135\ N.mm$

$PFy' = (383.048)\ (4)/\ \pi\ (702\text{-}302) = 0.121\ N/mm^2$

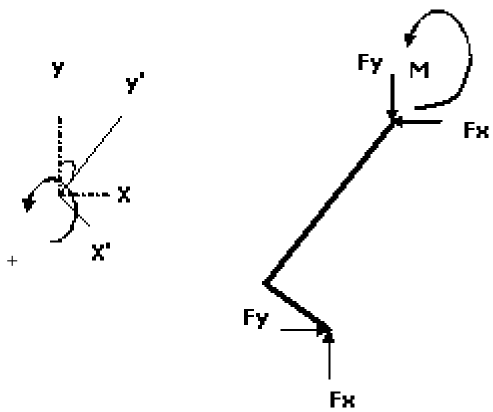


Figure (8) GRFs and reaction forces at push-off [8]

7. The Results and Discussions

Socket frame types and the gait phases are seen to affect the socket stresses. It should be noted that the base of polypropylene sockets that have different thicknesses has the same dimensions for all the sockets and **Fig.(9)** shows the socket base. A series of points on the socket at heights (10,100,150mm) for four sides (anterior, posterior, medial and lateral) of the socket are chosen to show the paths of stresses through the socket and **Fig.(10)** shows these locations.

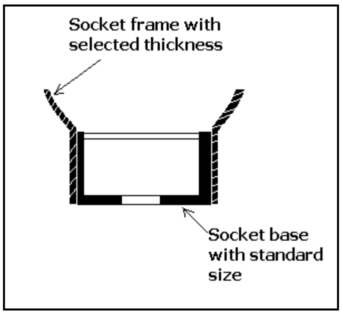
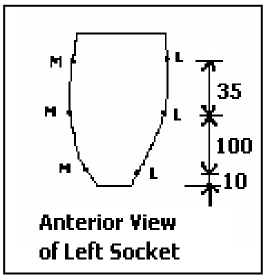


Figure (9) Polypropylene socket base



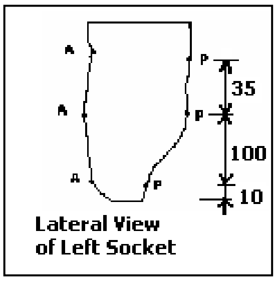


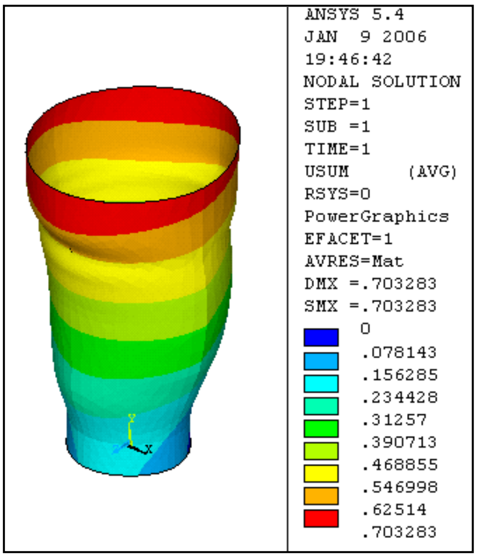
Figure (10) Locations of evaluated stresses on the sockets

Figures (12) to **(14)** show the von misses stresses and deformed shapes of polypropylene (5 and 3mm thickness) and the laminate sockets at phases of gait, heel strike, mid-stance and push-off. It can be seen that the highest stresses occur at heel-strike. Push-off phase has lower stresses than that occur during heel-strike and higher stresses than those occur at mid-stance phase. For the three sockets, the maximum stresses are produced at the base of the socket. For polypropylene socket, the peak stresses occur at the steel ring of its base.

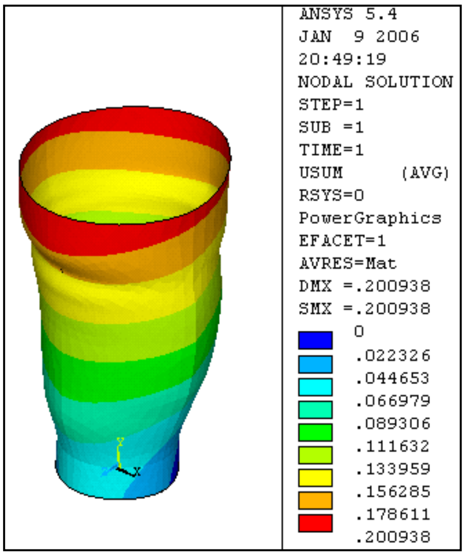
Table (5) shows the maximum deflection through the three gait phases for the three sockets. While **Tables (6)** to **(17)** show the stress values at different heights for four sides of the socket through the three phases of gait. These values are chosen to compare between the polypropylene at different thicknesses with laminate sockets.

The stress values for polypropylene (5mm thickness) and polypropylene (3mm thickness) have approximate values at the bottom base because of the structure of the socket base of polypropylene as shown in **Fig.(9)**. The differences in stress values appear in the socket frame which is attached to its base. Polypropylene (5mm thickness) has rather lower stresses than polypropylene (3mm thickness) and the laminated socket has the lowest stresses. The paths of stresses for the three sockets are found to have higher values at the bottom and lower values with increase in the height of the socket.

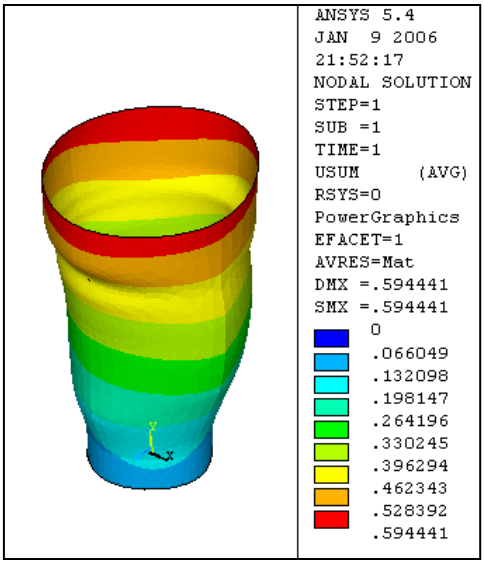
The difference in the deflection values for the three sockets is apparent. PP (5mm thickness) has lower deflection than PP (3mm thickness) and higher deflection than the laminate. The maximum deflection occurs at the PTB region of the socket for all sockets.



Deflection shape at HS

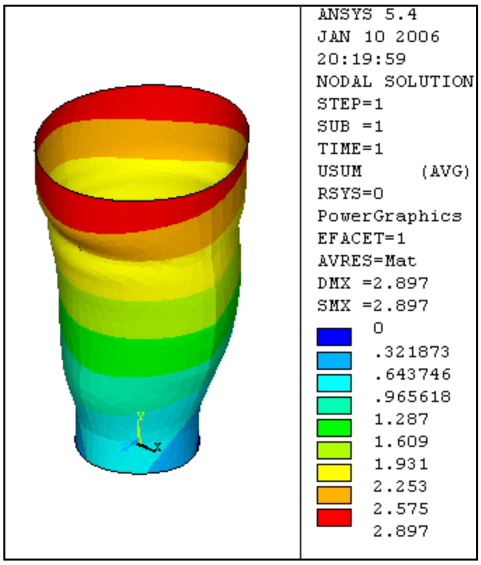


Deflection shape at MD

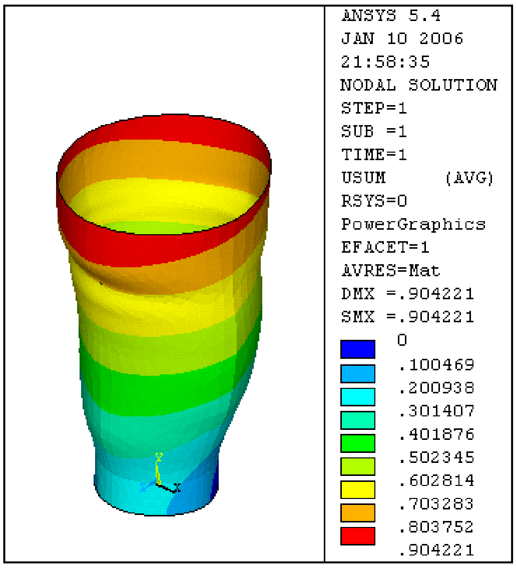


Deflection shape at PO

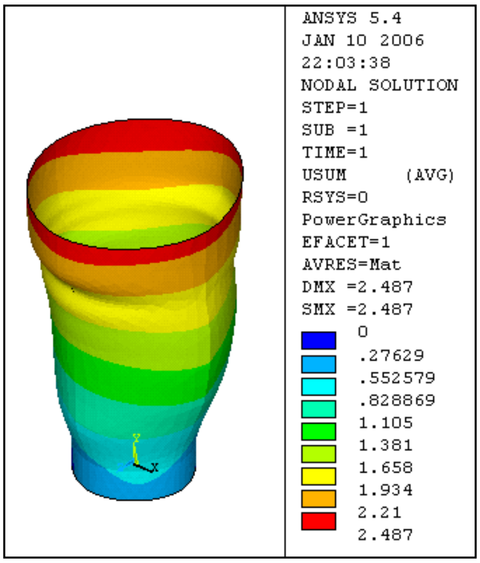
Figure (12) Deflection shapes of PP socket (5mm thickness) at gait phases



Deflection shape at HS

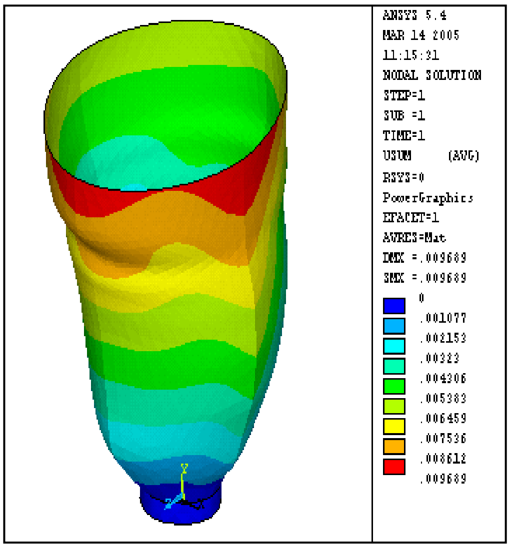


Deflection shape at MD

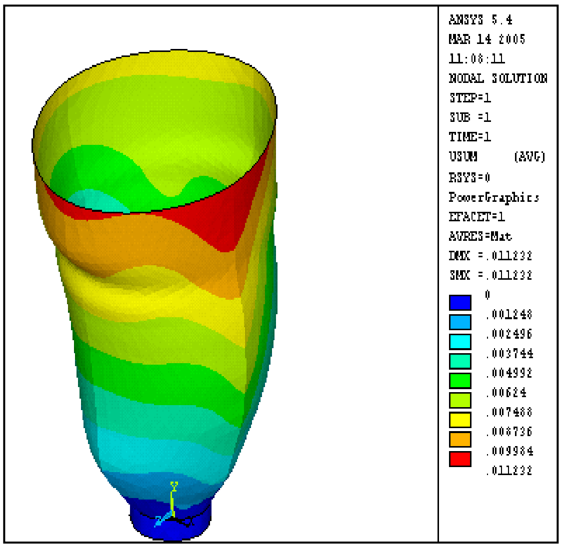


Deflection shape at PO

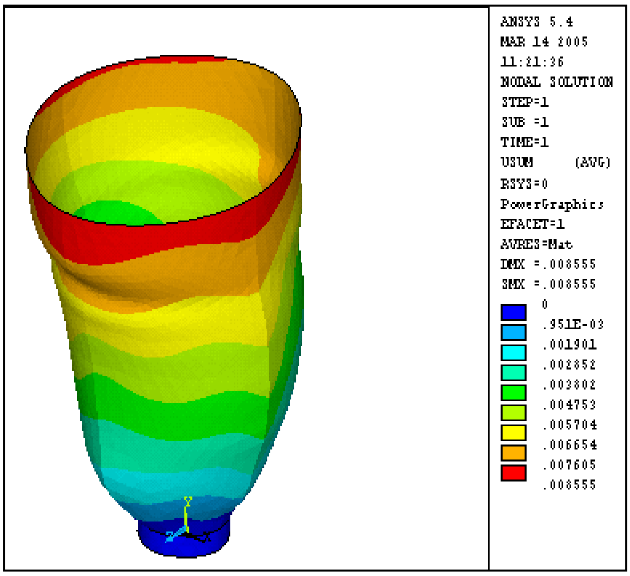
Figure (13) Deflection shapes of PP socket (3mm thickness) at gait phases



Deflection shape at HS



Deflection shape at MD



Deflection shape at PO

Figure (14) Deflection shapes of laminated socket at gait phases

Table (5) The maximum deflections of the three sockets during gait cycle

Socket Type	Maximum Deflection at HS (mm)	Maximum Deflection at MS (mm)	Maximum deflection at PO (mm)
PP(5mm)	0.764577	0.252467	0.65449
PP(3mm)	2.952	0.967273	2.542
Laminate	0.011232	0.009689	0.00855

Table (6) Stresses at the anterior region of the three sockets at heel strike

Height	Stresses for PP(5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	402.063	688.968	287
110	52.99	102.92	49.88
145	38.9	62.6	32.6

Table (7) Stresses at the posterior region of the three sockets at heel strike

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	288	628.9	108.8
110	48.8	129.3	62
145	18.38	39.29	9

Table (8) Stresses at the medial region of the three sockets at heel strike

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	289.2	398.8	211.2
110	59.8	120	52.7
145	28.98	88	18.282

Table (9) Stresses at the lateral region of the three sockets at heel strike

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	390.329	609	286
110	43.88	93	22.6
145	28.8	66.882	26.67

Table (10) Stresses at the anterior region of the three sockets at mid-stance

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	129.82	186.2	40
110	42.12	65.76	22.31
145	23.31	31.21	9.8

Table (11) Stresses at the posterior region of the three sockets at mid-stance

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	79.8	96.6	48.9
110	32.98	32.9	17.71
145	5.61	8.455	4.2

Table (12) Stresses at the medial region of the three sockets at mid-stance

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	68.3	98.6	65.2
110	19.8	36.8	18.27
145	9.696	18.082	4.6

Table (13) Stresses at the lateral region of the three sockets at mid-stance

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	119.896	129.9	111.289
110	18.7	38.285	15.573
145	4.86	10.069	4.23

Table (14) Stresses at the anterior region of the three sockets at push-off

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	389.3	629	186.8
110	39	90.03	26.6
145	11.8	26	9.8

Table (15) Stresses at the posterior region of the three sockets at push-off

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	20.99	528.9	116.617
110	43	168	42.71
145	16	32	12.26

Table (16) Stresses at the medial region of the three sockets at push-off

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	125.9	356	119.71
110	51	113	39.74
145	19	82	15.62

Table (17) Stresses at the lateral region of the three sockets at push-off

Height	Stresses for PP (5mm) (kPa)	Stresses for PP (3mm) (kPa)	Stresses for laminate (kPa)
10	292.9	480	210
110	42	82.1	25.6
145	22.5	62.2	13.57

8. Conclusions

From the previous discussion, the following points can be concluded:

1. For the three types of sockets, the stresses produced are maximum at the bottom base and decreasing with increasing height of the socket. The highest maximum stresses occurred during heel strike phase and their values do not exceed the yield stresses.
2. The laminated socket undergoes the least deflection because of it’s the high stiffness while polypropylene (3mm thickness) shows the maximum deflection which exceeding the critical value of (2mm). Polypropylene (5mm) shows medium value with respect its deflection. It should be noted that the region of the maximum deflection is the proximal edge of the socket (near the patellar region).

9. References

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List of Symbols

I: The distance between each transducer incorporated with the socket, (mm).

E: Young's Modulus, (MPa).

Fx: Horizontal force towards x-axis direction, (N).

Fy: Vertical force towards y-axis directions, (N).

L': Length of the shank, (mm).

D_i: Inner diameter of the socket base, (mm).

D_o: Outer diameter of the socket base, (mm).

FR: The resultant force of the distributed load at the socket base, (N).

P_{FR}: The average pressure produced by FR, (MPa).

$P_{Fy'}$: The average pressure produced by Fy', (MPa).

A: Area, (mm^2).

Abrivations

A: Anterior

GRF: Ground reaction force

M: Medial

L: LATERAL

P: Posterior

PP: Polypropylene

PTB: Patellar Tendom Bearing