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An experimental comparative study between polypropylene and laminated lower limb prosthetic socket

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Abstract:

Most researchers concentrate their studies on the design, stress and pressure distributions of the prosthetic socket. A little attention is considered for the stiffness of the various materials of the prosthetic sockets. Prosthetic laminated sockets in Iraq are costly to be manufactured while polypropylene socket is relatively cheap in comparing with the laminates.

Experimental study is conducted to compare the stiffness of five prosthetic sockets made of different materials. Compression, three point flexural and tensile tests are implemented by the Testometric machine. The laminate sockets give better results in compression than polypropylene. Polypropylene gives good results in bending compared with the laminate sockets. When the socket loads are mainly in compression i.e. the low activity level patients, it seems that any of the tested sockets could be used, however, when the load will be not only in compression but in flexion as well i.e. high activity patients, socket No.1 and 5 could be used.

Keywords: Prosthetic, Socket, Laminate, Polypropylene and Stiffness.

1-Introduction

The studies concerning the prosthetic socket are always about the pressure distribution of the socket, ignoring the materials of it. **Appoldt and Bennett[1]**, 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[2]**, investigated the difference in loading of four different material sockets, during stance phase, for the same patient. Their sockets were built with transducers incorporated. **Joshua et. al.[3]**, developed a new rapid prototyping method for fabrication of prosthetic socket. The system, referred to as SQUIRT shape, fabricates sockets by extruding a continuous bead of molten plastic and laying it down in the desired socket form. This technique eliminates intermediary steps (e.g., fabrication of plaster blanks and carving of socket positives) used in contemporary CAD/CAM of prosthetics, and enables the socket to be fabricated in a single operation. **Ross Stewart[4]**, devised an experiment to quantify the effectiveness of various suspension system. A transtibial limb was constructed to have similar anatomical feature and skin interface characteristics as an anatomical residual. To do this, vacuum, strap and anatomical suspension transtibial prosthetic socket could be done.

By using a tensile tester, a graph of the tensile force versus displacement was obtained. This work can be achieved to test the strength and stiffness of the material of the prosthetic socket. **Matt Fleming[5]**, conducted a similar experiment to Stewart's experiment, but in this case a real transtibial prosthetic patient is tested. The subject was cast and fitted with four different suspension systems. In the experiment each socket was donned by the subject and the displacement of the socket/liner was measured with various weights added to the set-up. **Arthur F.T. et. al.[6]**, reviewed the recent research literature on socket biomechanics, including socket pressure measurement, friction, computation modeling, and limb tissue responses to external loads and other physical conditions. It was noted that an understanding of comfort and optimal load transfer as patterns of socket interface stress could culminate in socket design. **Winson C.C. et. al.[7]**, perform a finite element analysis to determine the effect of monolimb flexibility on structural strength and interaction between residual limb and prosthetic socket.

2- Experimental Programme

2-1 Prosthetic Socket Manufacturing

The polypropylene and laminations are manufactured on plaster mold of cylindrical shape (100mm in diameter and 500mm in length). The mold is fastened to a vaccum device and covered with a nylon stockinette (woman socks). A heated sheet of polypropylene is fitted over the mold, while for laminations a PVA is pulled on the mold. The layup materials are then pulled onto the mold and placed under tension. Once all layup materials has been pulled onto the pipe, another PVA is pulled over the layup and tightened below the vaccum. At this point the layup is ready to laminate. The resin is added, then the vaccum is turned on.

Once polypropylene and laminations are completed, they are cut to test size, as shown in **Fig.1**. For the compression test a 50mm length of polypropylene and lamination is used whilst a 140mm length is used for the flexural test. The compression test gives an indication of comparative socket stiffness whilst the flexural test provides us the results which can be related to the clinical situation of socket loading. For tensile test, polypropylene material with 12 layers of laminate are chosen to compare between thermoplastic and composite material. **Table 1** shows the sockets for the testing purposes.

3- Experimental Procedure

Testing of polypropylene and lamination pieces are completed with the use of a Testometric testing machine. The compression and flexural test pieces are positioned in the testometric on the crosshead by suitable grips. 25000 N full scale load and 10mm/min crosshead speed are set. **Fig.2** and **Fig.3** shows the tested specimens used for compression and bending tests, while **Fig.4** shows the position of the sample for the flexural test. Calculations of the flexural strengths of the tested sockets are shown in the **Appendix**.

D638(ASTM standard) is used for sizing the polypropylene and laminated samples for tensile test. **Fig.5** shows the sizes for polypropylene and No.5 socket (12-layers of laminate). For polypropylene material, the necking of the test piece should be occurred during 100 seconds. Therefore, trial pieces were tested at different cross head speeds to get the correct results. For the laminate piece, the cross head speed is 5mm/min.The tensile tested pieces for No.1 and No.5 sockets are positioned on the testometric machine by a suitable grips.

4-Results

From **Table 2** and **Fig.6**, it can be noticed that socket No.5 has the largest compressive stiffness, followed by sockets No.4, No.3, No.1 and No.2 respectively. The difference in compressive stiffness between the laminated sockets is not significant, while there is relatively apparent difference between sockets No.5 and No.1. This is due to the fibers strength in the direction of the load.

For the fracture compression stresses , there are differences in this aspect. Sockets No.1, No.4 and No.5 do not fracture, and they tolerate larger than 25000 N as compression loads. While No.2 and No.3 sockets tolerate 21000 N and 23000 N respectively. There is a difference in the nature of the fracture of polypropylene and laminated socket. For polypropylene, failure starts with stress whitening phenomenon in the socket with final fracture in the bonding region, While for laminated socket, fracture starts with resin failure.

For flexural bending test, polypropylene sample deflects to more than 4mm and after unloading the bending load, the sample seems to return to its original shape with small plastic deformation. For laminates samples, failure is apparent by fracturing the resin.

From **Table 2** and **Fig.7**, sockets No.5 and No.1 have the largest flexion stiffness, followed by No.4, No.3 and No.2 sockets.

Fig.8 shows the experimental results of the tensile test for socket No.1 and No.2. For polypropylene material (socket No.1), the material properties are,E=1.235 GPa, $\sigma_{ult.}$ =33.5 MPa, σ_y = 25 MPa**.** The polypropylene does not have a well-defined yield point, and consequently the graphical method of offset method is used to define the yield point. Normally, a 0.2 % strain is chosen, and from this point on the strain axis, a line parallel to the initial straight line portion of the stress-strain diagram is drawn. The point where this line intersects the curve defines the yield strength. It is found that polypropylene is an extended material under tensile load or No.5 socket, the material properties are, E= 2.092 GPa, $\sigma_{ult.}$ =48.97 MPa. The socket No.5 (laminated socket) undergoes a little deformation before its final fracture because of its brittleness.

5-Discussion

The prosthetists consider laminated sockets stronger than polypropylene in all mechanical properties. Through the tests, it is found that compressive stiffness of lamination is larger than polypropylene with not very high difference. From **Fig.5** it should be noted that the socket No.1&2 (polypropylene) have more deflection than the rest sockets(laminations), and this means that the ductility of polypropylene is greater than laminations. This is a useful factor if we take into considerations the pressure relief regions of patient's stump(truncated part of his leg). For the bending test, it should be noted from **Fig.6** that all the sockets in the bending test pass through three stages:

1. Linear behavior at the first stage.
2. Appearance of the effect of the sample slipping over the supports as the deflection increases at the second stage. It should be noted that the sample slipping does not affect the stiffness which is evaluated at the first stage.
3. Then, failure of the sample by the effect of the maximum load.

Socket No.1(polypropylene,5mm) has better flexural stiffness than the tested laminated sockets except socket No.5 which has a very little higher stiffness than socket No.1 socket. In the bending test, the stiffness of laminated sockets depends upon the types and the amount of the resin in addition to the fibers. The problem is that the manufacturers in the medical rehabilitation centers do not use the sufficient amount of resin because of its high cost. While the modulus(stiffness) of a laminate depends upon fiber and resin volume fractions. It should be noted that stiffness of sockets No.5 and No.1 are approximate.

6-Conclusions

1. When the socket loads are mainly in compression i.e. the low activity level patients, it seems that any of the tested sockets could be used, however, when the load will be not only in compression but in flexion as well i.e. high activity patients, socket No.1 could be used.
2. In Iraq, polypropylene is good selected material compared with laminates, because of its good mechanical properties and cost.

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Appendix

Calculations Concerning Flexural Tests

Fig.9 shows the cross-sectional of the bending sample. The equations used in calculation of the bending strenfths are as follows:

$Xc= (2/3)(R)(\sin\alpha/\alpha)\ (1-t/R+(1/(2-t/R)))$

$x1= R-Xc$

$x2= Xc-(R)(\cos\alpha)$

$Iy=(R^4-r^4)/8(2\alpha+\sin 2\alpha)$

$Ic=Iy-(R^2-r^2)(\alpha)(Xc^2)$

$\sigma t= (M)(x1/Ic)$

$\sigma c= (M)(x2/Ic)$

Table 1 The test sockets

Socket No.	Material
1	5mm polypropylene
2	2mm polypropylene
3	Perlon (10-layers)with orthocryl resin.
4	Nyglass(8-layers)with orthocryl resin.
5	Perlon(2-layers),nyglass(2-layers),fiberglass(2-layers), nyglass(2-layers),fiberglass(2-layers) and perlon(2-layers)with polyster resin.

Table 2 Summary of results for experimental tests

Socket No.	Thickness mm	Compression test		Flexural bending test		
		Cross sectional area mm^2	Compressive stiffness(Kc)N/mm	Flexural stiffness(Kb)N/mm	σt MPa	σc MPa
1	5	1884.956	8333	32.4	30.17	39.429
2	2	779.114	7222	16.67	27.11	41.73
3	2	779.114	9000	18.5	24	36.96
4	3	1178.097	9524	20	32.58	46.63
5	3.5	1280.98	10364	33.33	44.43	62.38

Table 3 The parameters used in finding tensile & compression bending stresses for bending test

Parameter	Socket No.1	Socket No.2	Socket No.3	Socket No.4	Socket No.5
R mm	62.5	63	63	64	60
r mm	57.5	61	61	61	56.5
α degree	20.609º	20.438º	20.438º	20.105º	21.51º
Xc	58.748	60.698	60.698	61.237	56.908
x1	3.75	2.3	2.3	2.763	3.091
x2	4.9	3.54	3.54	3.954	4.34
Ic	714.576	148.45	148.45	264.961	373.935
Fmax N	230	70	62	125	215
M N.m	5750	1750	1550	3125	5375

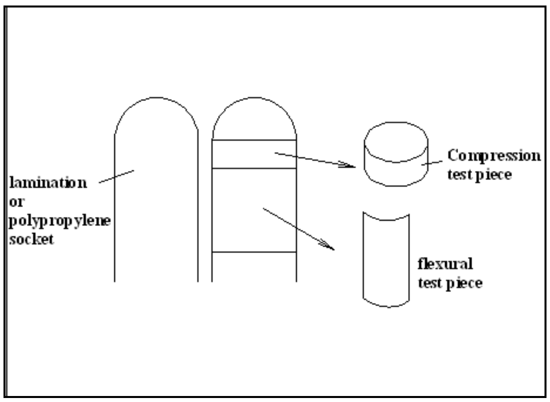

Fig.1 The socket and the test pieces

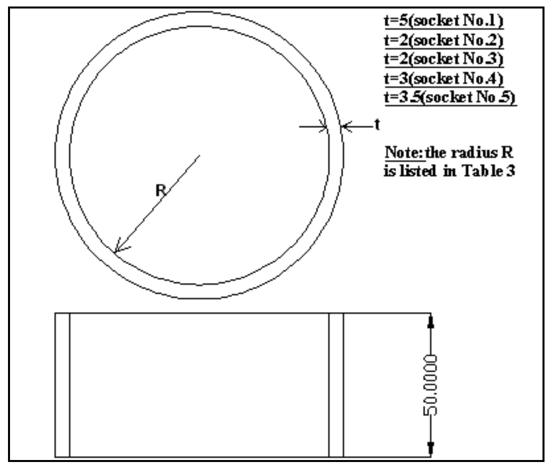

Fig.2 Compression test specimen

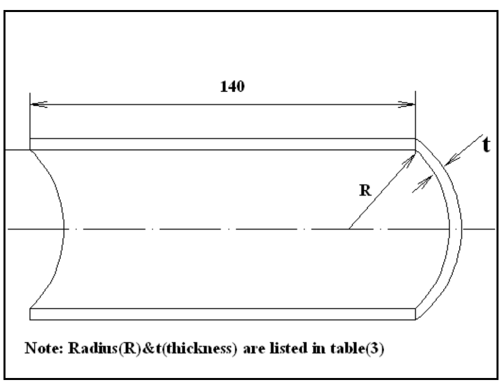

Fig.3 Bending test specimen

Fig.4 Bending test of socket

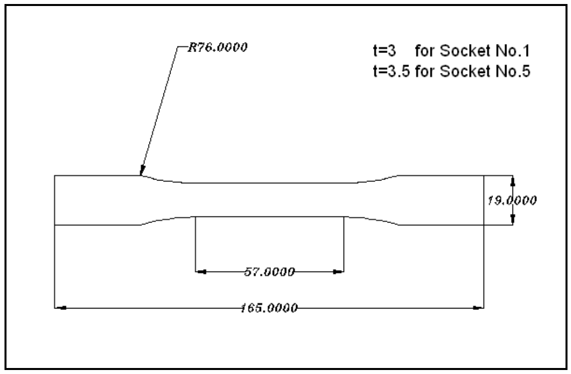

Fig.5 Dimension of tensile specimen(D638)

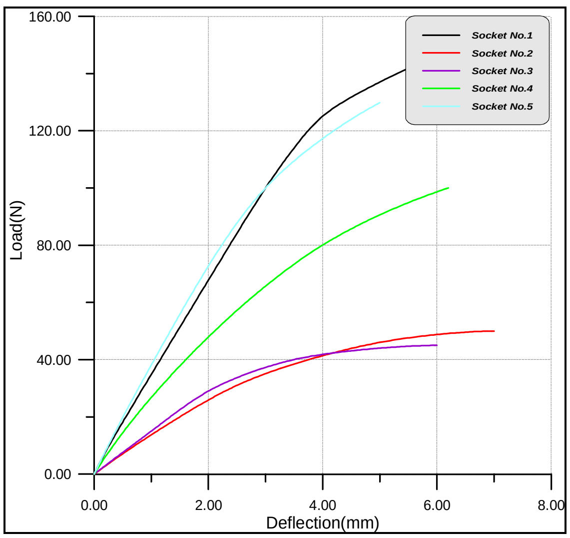

Fig.6 Compression graphs for all sockets

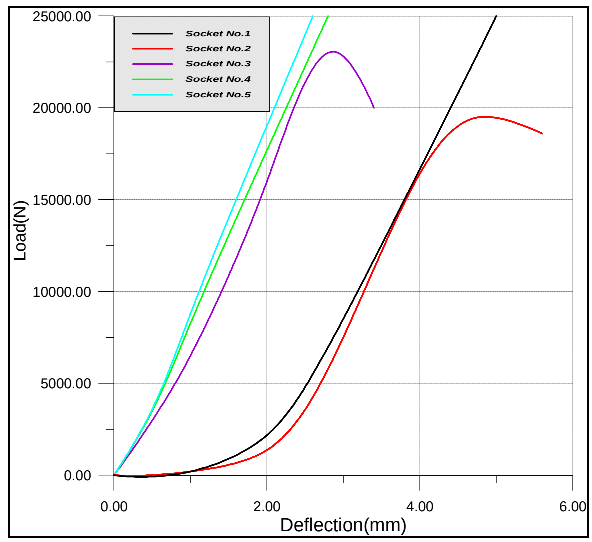

Fig.7 Flexural bending graphs for all sockets

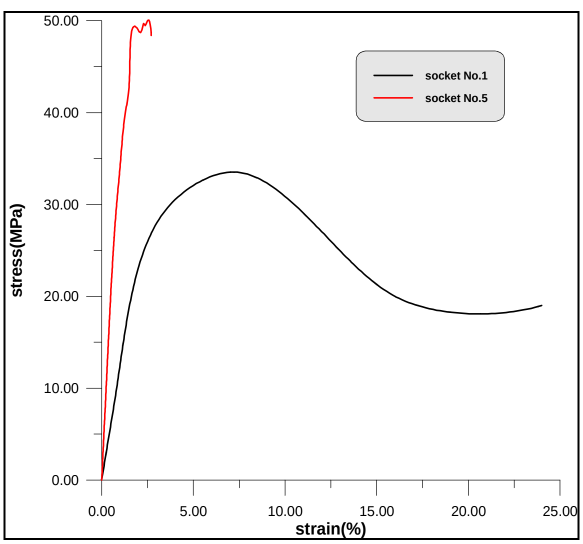

Fig.8 tensile test for socket No.1&5

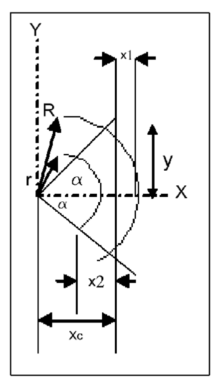

Fig.9 Cross section of the bending sample

دراسة تجريبية لمقارنة بين وقب البولي بروبلين والمواد المركبة للطرف السفلي البديل (الصناعي).

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الخلاصة:

يرك ز الباحثين في دراساتهم عل ى تصد ميم و توزي ع الاجه ادات و الضد غوط للوق ب الصد ناعي البديل (ن ط رف الانس ان المبتور) ،و يكون الاهتمام قليلاً بجساءة(stiffness) المواد المصنوع منها الوقب البديل. ان سعر الاوقاب الطبقية(المصنوعة م ن عدة طبقات من الالياف)البديلة يكون غالياً جداً مقارنة بالوقب المصنوع من مادة البولي بروبلين الذي يكون سعره زهيداً.

جُريت دراسة عملية لغرض مقارنة جساءة خمسة أنواع من الاوقاب البديلة مصنوعة م ن م واد مختلفة أُج ري اختب ار الض غط، واختبار الانحناء و الشدّ بماكنة Testometric. من خلال النتائج وجد أنه الوق ب الطبقي يمتلك مقاوم ة للتش وه الن اتج م ن الحم ل الانضغاطي اكبر من تلك للبولي بروبلين(جساءة الوقب الطبقي في حالة الانض غاط اعل ى م ن تل ك للب ولي ب روبلين)و أن الأخي ر يمتلك مقاومة للتشوه الناتج من الحمل ألانثنائي اكب ر م ن ك ل ان واع الوق ب الطبق ي ع دا الوق ب رق م ٥.ان الاش خاص ذوي فعالي ة المشي الواطئة يكون اغلب التحميل عل ى الوق ب انض غاطي وبه ذا يمك ن اس تخدام اي م ن الاوق اب لان ه ق يم الجس اءة الانض غاطية م ا متقارب ة م ع افض لية للوق ب الطبق ي، بينم ا الاش خاص ذوي الفعالي ة العالي ة ال ذي يك ون اغل ب التحمي ل عل ى الوق ب انثنائي(flexural)يتم استخدام الوقب الطبقي رقم ٥ (الذي يمتلك اعلى الطبقات) ووقب البولي بروبيلين ذو سمك ٥ملم.