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Design and Analysis of New Prosthetic Foot.

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Abstract:

There is a variety of artificial foot designs variable for use with prosthetic legs . Most of the design can be divided into two classes, articulated and non-articulated feet. one common non-articulated foot is the SACH . The solid ankle cushion heel foot referred to as the SACH foot has a rigid keel .

One key or the key factor in designing a new prosthesis is in the analysis of a patients response .

This view is the most important because if the foot does not provide functional , practical or cosmetically acceptable characteristics the patient will not feel comfortable with the prosthesis , therefore design and manufacturing a new foot is essential, this foot made from polyethylene, its different shape and characteristics

The characteristics deemed important by patients in achieving natural gait motion include:

Dorsiflexion
Energy return
Fatigue test

In this study, including all these characteristics test, design fatigue foot tester according to ISO 10328 and design new foot .Also, the testometric crosshead was modified to find dorsiflexion angle and energy return .The fatigue criteria for polymer was proposed, in mathematical solution.

Finally , the characteristics of SACH foot was compared with new foot by mathematical solution and used visual basic program and experimental method by different tests. From these test that the new foot is better than SACH foot for all test .

Keywords: Prosthetics foot , Fatigue, Dorsiflexion ,Energy return and SACH foot .

Introduction:

Amputation of a lower limb is most commonly performed due to landmines or disease of the limb. The two most often performed amputation procedures are truncation of the femur bone Above the Knee (AK) and truncation of the tibia bone Below the Knee (BK).

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-phalange joints), and the loss of the muscles of the anterior and posterior compartments of the shank. The levels and classification of below the knee amputations are shown in figure(1-B) .[1]

BK prostheses, figure (1-A) are typically comprised of four major components these are: Socket, Pylon, Foot prosthetic and Couplings.

The main purpose of a prosthetic foot, shank and socket is to provide a means of replacing the lost structure and function of the skeleton and muscles of the foot, ankle and shank. [2]

There are different type of foot but the one of most commonly is called (SACH foot) since it was developed in the early 1950`s by the university of California. The numerous investigation have analyses compared different type of prosthetic feet by means of mechanical testing , gait analysis , ground reaction force , energy return and fatigue test . The durability and fatigue characteristics of prosthetic foot are very important when deciding which type of prosthetic foot to prescribe for a particular patient . there for a number of studied have cycled prosthetic feet to assess their durability and wear a cyclic tester which mimics natural gait .[3]

In 1975 **Daher**[4]conducted an extensive investigation in which nine types of SACH feet were subjected to cyclic testing to assess the durability of the materials and design of the foot Unless breakdown occurred.

Wevers and Durance[5] in 1987 also conducted dynamic testing on prosthetic SACH feet, but they loaded the whole trans-tibia prostheses not the foot alone.

A report by Kabra et al [6] utilized a simple , low cost machine to fatigue the Jaipur foot , similar to Toh's device.

Francis J. Trost [7] investigated by using different material that stored energy when compressed by the body during early stance phase.

Lehmann and Colleagues within two separate reports[8], [9], conducted a similar analysis determining the load vs. deflection (compliance) of prosthetic feet via a static loading machine.

The New Design Foot:

There are numerous prosthetic foot designs available these prosthetics feet serve basic functions which include: support the body against gravity during standing and walking ;

absorb shock during heel contact and in some cases mimic metatar sophangeal function during the stance phase of gait , preventing the fatigue failure , principle of storing energy as the stance limb accepts body weight and returning this energy as the foot lift off the ground and good lifts off the ground and good dorsiflexion and eversion .The shape of new foot dependent to dorsiflexion angle and the energy return .

The new design in consideration of the need of a lighter foot for the elderly amputee population and its relative low cost.

The shape at point R of the foot ankle complex creates a joint with an axis of rotation that changes location during the stance phase as the body's center of mass proceeds forward over the foot figure(1-A) . The shaped ankle joint can be described C curve and shaped of end keel can be described also C curve . At the end of mid stance C curves closed and touch the top of the forefoot section . The new design foot is made of a flexible material (polyethylene)this allow the forefoot of the prosthetic foot to bend and the fatigue limit of this material was good.

It is possible to design a simple , practical foot that achieves very specific performance criteria. Currently , the cause of failure of most prosthetic feet used in developing countries is the breakdown of the prosthetic keel due to excessive wear of the cosmetic covering for the foot, usable with or without a cosmetic cover, the life of a foot is increased .

The new foot is tested and checked all properties " dorsi-flexion, and fatigue failure" experimentally in the result section, in this study must be check analytically by used fatigue criteria. The shape of new design foot is difficult to be achieved foot properties or to mimic normal foot by size and comfortable.

To find the life of new foot by proposed a new fatigue criterion for polymer:

$$S_f = 10^C N^b \qquad \text{(general equation)}$$

$$Log(S_f) = C + bLogN \qquad \dots(1)$$

b is represented slope of Equation (2)

$$b = Log\left(\frac{S_{f1}}{S_e}\right)^{\frac{1}{Log\left(\frac{N_1}{N_2}\right)}} \qquad \dots(2)$$

Where N1 , N2,Sf1 and Se are No of cycle at high fatigue strength , No of cycle at low fatigue strength , high fatigue strength and low fatigue strength shown in figure (5),C is constant equation(2)at N1.

$$C = LogS_{f1}^{\frac{-LogN_2}{Log\frac{N_1}{N_2}}} + LogS_e^{\frac{LogN_1}{Log\frac{N_1}{N_2}}}$$

$$C = Log\left(S_{f1}^{\frac{-LogN_2}{Log\frac{N_1}{N_2}}} \times S_e^{\frac{LogN_1}{Log\frac{N_1}{N_2}}} \right) \qquad ..(3)$$

$$N_l = \left(\frac{\sigma_a}{10^C}\right)^{\frac{1}{b}}$$

$$N_l = \left(\frac{\sigma_a}{(S_{f1}^{\frac{-LogN_2}{Log\frac{N_1}{N_2}}} \times S_e^{\frac{LogN_1}{Log\frac{N_1}{N_2}}})} \right)^{\frac{Log(\frac{N_1}{N_2})}{Log(\frac{S_{f1}}{S_e})}}$$

$$N_l = \left(\frac{\sigma_a^{Log(\frac{N_1}{N_2})} S_{f1}^{LogN_2}}{S_e^{LogN_1}} \right)^{\frac{1}{Log(\frac{S_{f1}}{S_e})}}$$

$$N_l = \left((\frac{\sigma_a}{S_e})^{LogN_1} \times (\frac{S_{f1}}{\sigma_a})^{LogN_2} \right)^{\frac{1}{Log(\frac{S_{f1}}{S_e})}} \quad .(4)$$

$$S_e = K_a K_b K_c K_d K_e K_f S'_f \quad ..(5)$$

Where K_a , K_b , K_c, K_d, K_e are factors of : surface, size , reliability , temperature , modifying stress concentration and miscellaneous respectively, [10] :

$$K_a = K_c = K_d = K_f = 1$$

$$K_b = \begin{pmatrix} 1 \longrightarrow d \le 8mm \\ 1.189d^{-0.097} \longrightarrow 8mm < d \le 250mm \end{pmatrix} \quad ..(6)$$

When a noncircular section such as a rectangular section:

$$d = 0.808(hb)^{\frac{1}{2}}$$

$$K_f = 1 + q(K_t - 1)$$

$$K_e = \frac{1}{K_f} \quad ......(7)$$

Where: Ke is modifying factor for stress concentration, Kf is fatigue stress concentration factor, q is notch sensitivity and Kt is stress concentration factor.

The stress at point T :

$$\sigma max = \frac{P_1 L_1 6}{ba^2}$$

$$\sigma min = 0$$

$$\sigma a1 = \frac{\sigma max - \sigma min}{2} = \frac{P_1 L_1 3}{ba^2} \quad ...(8)$$

The stress at point R :

$$\sigma max = \frac{P_1}{bc} + \frac{P_1 L_2 6}{bc^2}$$

$$\sigma min = \frac{P_2}{bc} - \frac{P_2 L_3 6}{bc^2}$$

$$\sigma a2 = \frac{P_1}{2bc} + \frac{P_1 L_2 3}{bc^2} - \frac{P_2}{2bc} + \frac{P_2 L_3 3}{bc^2}$$

$$\sigma a2 = \frac{P_1}{2bc} + \frac{P_1 L_2 3}{bc^2} - \frac{P_2}{2bc} + \frac{P_2 L_3 3}{bc^2} \quad ...(9)$$

$$N_l \ at \ point \ T = \left((\frac{\sigma_{a1}}{S_{eT}})^{LogN_1} \times (\frac{S_{f1}}{\sigma_{a1}})^{LogN_2} \right)^{\frac{1}{Log(\frac{S_{f1}}{S_{eT}})}}$$

$$N_l \ at \ point \ R = \left((\frac{\sigma_{a2}}{S_{eR}})^{LogN_1} \times (\frac{S_{f1}}{\sigma_{a2}})^{LogN_2} \right)^{\frac{1}{Log(\frac{S_{f1}}{S_{eR}})}} \quad (10)$$

Where SeT, SeR are fatigue limit at T point and point R respectively.

Comparing between NLT and NLR then choose minimum number of cycle .

These equations are used to build the visual basic program , the windows of program as shown in figure (5)

Experimental Work:

Many experimental tests are recommended to the manufacture and design the foot. The tests were compared with the theoretical procedure to show the difference between the experimental and theoretical results.

1- Tensile test and fatigue test for polyethylene.
2- Design and manufacturing fatigue foot tester.
3- Design and manufacturing new foot.
4- Dorsiflexion, energy return and fatigue foot test to be achieved.

Tensile test and s-n curve test:

The theoretical and experimental calculations depend on the mechanical properties of the material these can be found from the tensile test of standard specimens according to the recommendation of ASTM D-638.[11]

The fatigue test (S-N curve) for polyethylene according to ASTM D 671-[12]

Design And Manufacturing Of The Fatigue Foot Tester (FFT):

The fatigue foot tester, figure (2), was designed and built using the functional requirements outlined in ISO standards .

According to ISO 10328[13] standards , forces must be applied at 15o and anterior to tibia axis upon heel strike and 20 o posterior to the tibia axis upon toe off . The fatigue Tester is designed to simulate human gait by alternating the heel and toe loadings.

Mechanical And Electrical component For (FFT):

Each cycle test station consists of :

1- Pair of pneumatic cylinders (70.3 mm)bore , 90.2 mm stroke , single acting .
2- A prosthetic foot – shank assembly .
3- Support brackets for the shank .
4- Counter to record the number of test cycles completed .
5- All of the components mentioned above mounted onto frame.
6- Air compressor (120 L) with regulator.
7- Air filter (Air mixture filter).
8- Timer (to increase or decrease frequency of cycle)
9- Pair of solenoid valve .
10- Control system , gives alternative signal to the solenoid valve .

The value of applied load according to ISO 10328 for amputee 60 Kg , that mean the ground reaction force about 753 N .

In order to find a specific force value , various combinations of compressor pressure can be determined form :

$$F = \frac{\pi}{4}(D_{bore})^2 P \quad \dots (11)$$

Where F is the desired force , Dbore is the diameter of the bore .

A calibration table , comprising the desired force values for the various combinations can be process by use load cell and reader.

Design And Manufacturing Of New Foot:

In Iraq and most of country, the SACH foot is common foot but this foot had small dorsiflexion from ankle , it's depended to the end of forefoot bending , therefore its discomfort able.

From forty state of foot failure in Baghdad centre of artificial limb for SACH foot is appeared the failure region midway between the head of metatarsals and the distal end of the phalanges that region is end of keel and it's applied the alternative load. Its failure by fatigue.

The SACH foot in Iraq it's from different company such as Germany's foot (ATTO BOCK COMPANY) and French's foot, There are no one design or manufactured this foot or any foot in Iraq.

Disposal of the disadvantage for SACH foot , by designing and manufacturing new design foot, it's depended on dorsiflexion and mechanical properties for material and prevent fatigue failure.

The new foot design is made from polyethylene , that material is high endurance limit and good flexibility respect of the applied load according to the gap above keel and ankle .The heel region and base is manufactured by rubber foam .

The New Foot Testing :

A-Fatigue Foot Test

The SACH foot is placed on fatigue tester to obtained life of foot .This procedure was applied to new foot to comparing between two life .

The load is alternative as simulate normal gait , the first piston struck heel foot and second piston struck forefoot were sequenced. A counter in fatigue foot tester is recorded the number of strike.

To control on frequency of strike by used frequency meter as according to ISO standard

B- Dorsiflexion test:

To complete the dorsiflexion test must be manufacturing the triangular wood and supported with ruler graded [14].This piece of wood is put in testometric machine. It's replaced under crosshead.

The foot is touched the triangle wood and applied force , this force simulated ground reaction force . dorsiflexion test is applied in two different of foot , SACH foot and new design foot and comparison with normal human foot , figure (4).

The amount of dorsiflexion as related to vertical displacement is therefore determined by the toe lever of the foot , where the toe lever is distance the attached pylon to pivot corresponding to the ball of the foot.

$$\phi = \tan^{-1}\frac{Y}{X} \qquad \dots (12)$$

C- Stored Energy Returned

In this part compares the mechanical capabilities for storage and release of energy of SACH foot and new design foot by examining their force –deflection characteristics, under certain given conditions.

The energy stored and released could be express as an efficiency when compared to the ideal situation [15].Energy storing potential can thus be defined in the following way[16]

$$Energy\ storing\ potential\ \% = \frac{Area\ P}{Area\ T}\times 100 \qquad (13)$$

Area P: actual energy stored by material at limit. Area T: Ideal energy stored at force 753 N

By recording the curve for loading and unloading , the hysterics loop for the material can be determined giving a percentage of energy returned .

$$Energy\ return\ efficiency\ \% = \frac{Area\ B}{Area\ A}\times 100 \qquad (14)$$

The stored energy returned is relevant only to the value of load (60) Kg and dorsi-flexion (5o) as it is dependent on the energy storing potential at these condition .

$$Stored\ energy\ returned = Energy\ storing\ potential \times \frac{Energy\ return\ efficiency}{100} \qquad (15)$$

The Results And Discussions:

Theoretical Results For New Foot:

From fatigue equations, we obtain the life of new foot , The life of new foot is 675387 cycle when a= 37 , b=75 , c =31 , Sf1= 18.1 MPa , Sf2=4.7 MPa , N1= 407 cycles and N2=10000000 cycles

This result is represented by the visual basic program , figure (2)

Experimental Results:

The mechanical properties of all material and The fatigue test(S-N) curve for polyethylene are shown in table (1)and table(2). The experimental results for foot are including:

1- Dorsiflexion And Energy Return:

Figure (6-A) and figure (6-B) show the results of the dorsi-flexion angle and energy storing potential respectively for SACH foot and new foot. Figure(7-A) and figure(7-B) show the hysterics loop for the materials of foot.

The dorsiflexion angle experimentally is obtained by video (camera) then it's plot with gait cycle . The maximum dorsiflexion angle at 75 % of stance phase a bout 5o , 1.8 ^{o} , 3.7^{o} for

SACH foot and New ,normal human foot foot respectively.

The stored energy return are 13.14 , 58.9 for SACH foot and NEW foot respectively , table (3). From the shape of new foot explained two curve in ankle and keel end that help , in addition , the new foot was made from polyethylene that material was good for flexibility .

2- Fatigue Foot Tester Results :

In order to determine the validity of the new foot fatigue tester in comparison to other tester currently being used , the industry standard SACH foot was tested in one of the test stations in order to determine its time failure .

The SACH foot that was deemed a failure at 112,786 cycles was stored for approximately 24 months prior to testing , however , the SACH foot removed from the tester at 896,213 cycles was placed on the tester within a few months of manufacturing . This may indicate the material degradation in a factor in the life expectancy of SACH feet, however, Further testing would have to be under taken.

The new foot failure occurred in one specimen at 1.233.417 cycles. The centre of curvature of beach marks indicate the origin of the failure and direct the investigator that served as crack nucleation sites . Smaller location of crack propagation were evident however are believed to be secondary sources of failure.

There are different value between theoretical results and experimental results for new foot because the fatigue criteria in polymer depend on application and the mathematical solution depend on assumption .

Conclusion:

The new foot was easily the most suitable foot for the patient conditions chosen both in energy storing potential and energy return efficiency. The dorsiflexion angle for new foot better than SACH foot .

By comparing the characteristics exhibited by prosthetic foot to these of a human foot , a selection of these prostheses was undertaken based on their favorability to the characteristics of a human foot , the new foot is a good characteristics .

The SACH foot that was deemed a failure at less number of cycle when it was stored for approximately 24 months prior to testing . The new foot is a good life compared with SACH foot.

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TABLE (1) MECHANIAL PROPERTIES FOR POLYETHYLEN AND RUBBER FOAM

MATERIAL	σ_y (MPa)	σ_{ULT} (MPa)	E (Gpa)
POLYETHYLEN	16.52	22.3	1.23
RUBBER FOAM	5.3	8.2	0.58

TABLE(2) S-N DATA FOR POLYETHYLEN

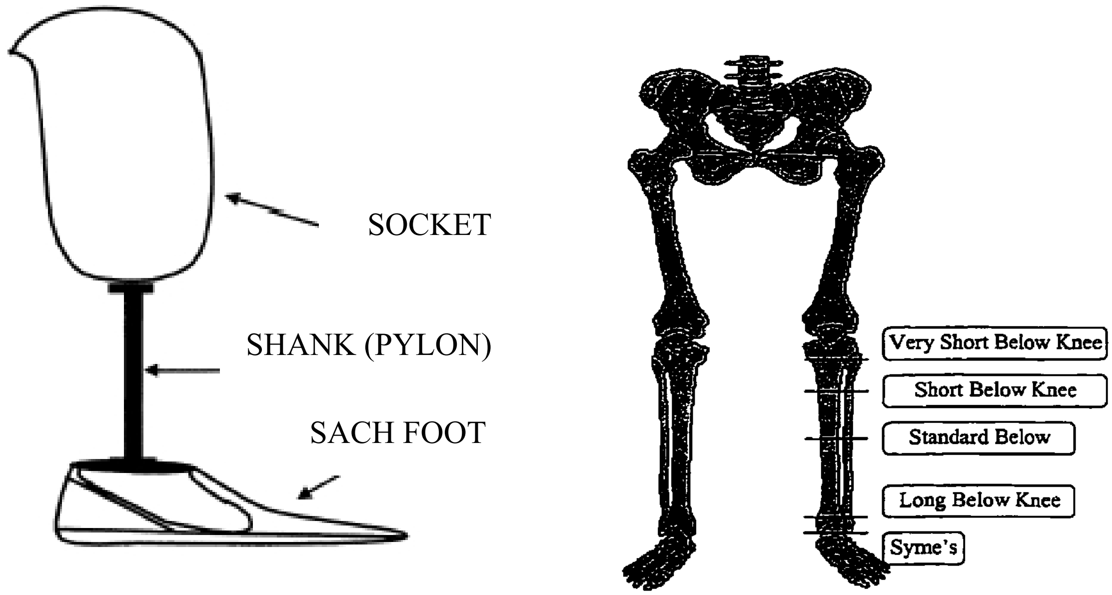
MATERIAL	S_{f1} (MPa)	S_{f2} (MPa)	N1 (CYCLE)	N2 (CYCLE)
POLYETHYLEN	17.16	3.82	407	10000000

TABLE (3) DORSI-FLEXION AND ENERGY RETURN

NAME	**DORSI-FLEXION ANGLE**	**ENERGY STORING POTENTIAL%**	**ENERGY RETURN EFFICICENCY%**	**STORED ENERGY RETURN %**
SACH	1.9^{O}	24.2	54.4	13.14
NEW FOOT	4.2^{O}	73.4	80.3	58.9

TABLE (4) LIFE OF DIFFERENT FOOT

NAME	LIFE OF FOOT (CYCLE)	
	THEORITICALLY	EPERIMENTLLY
SACH (OLD)	___________	112,786
SACH (NEW)	___________	896,213
NEW FOOT	752,342	1,233,417



A B

FIGURE (1) A-COMPONENT OF PROSTHETIC BK, B –PROSTHESES LEVELS

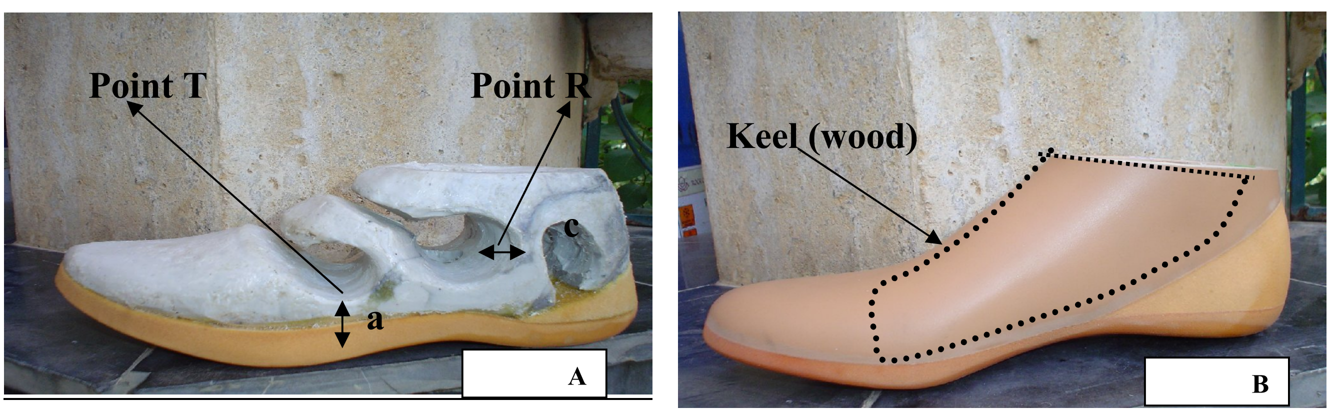
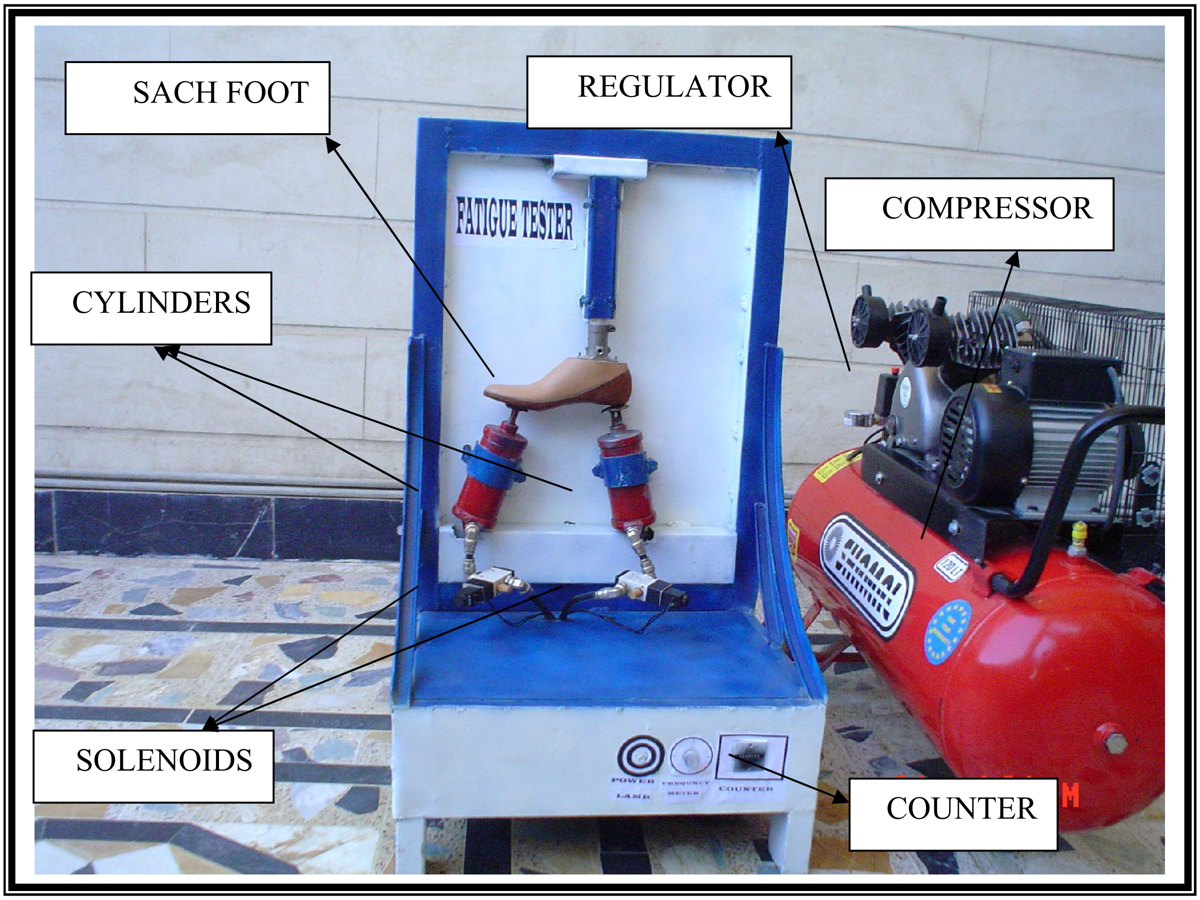
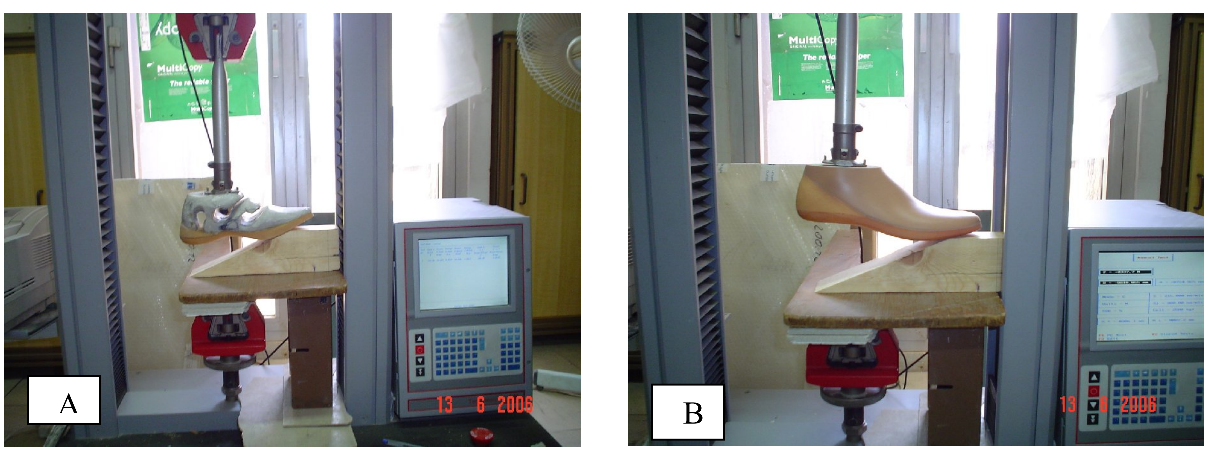


FIGURE (2) :A- NEW FOOT , B- SACH FOOT



FIGURE(3) FATIGUE FOOT TESTER



FIGURE(4) DORSIFLEXION AND ENERGY RETURN :

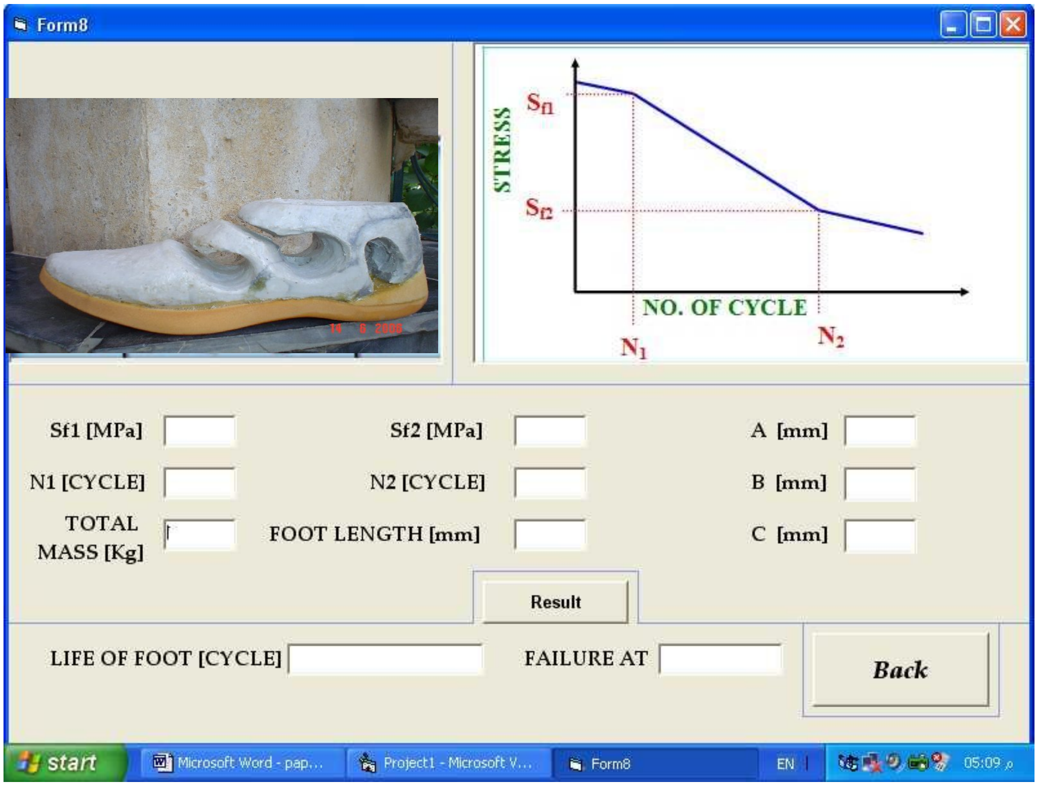
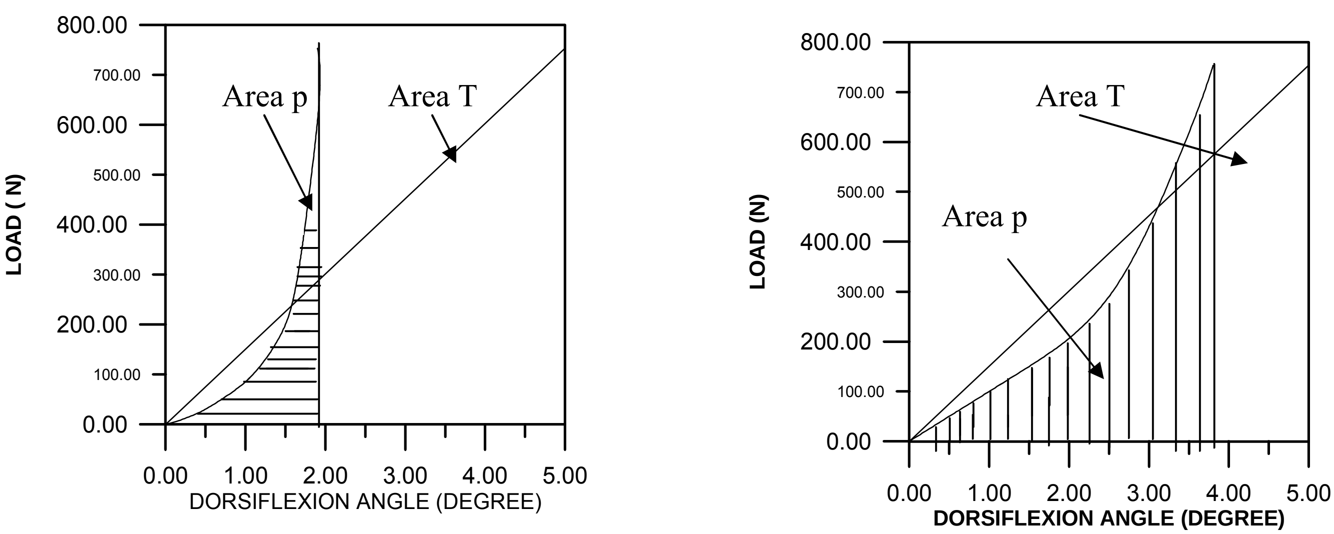
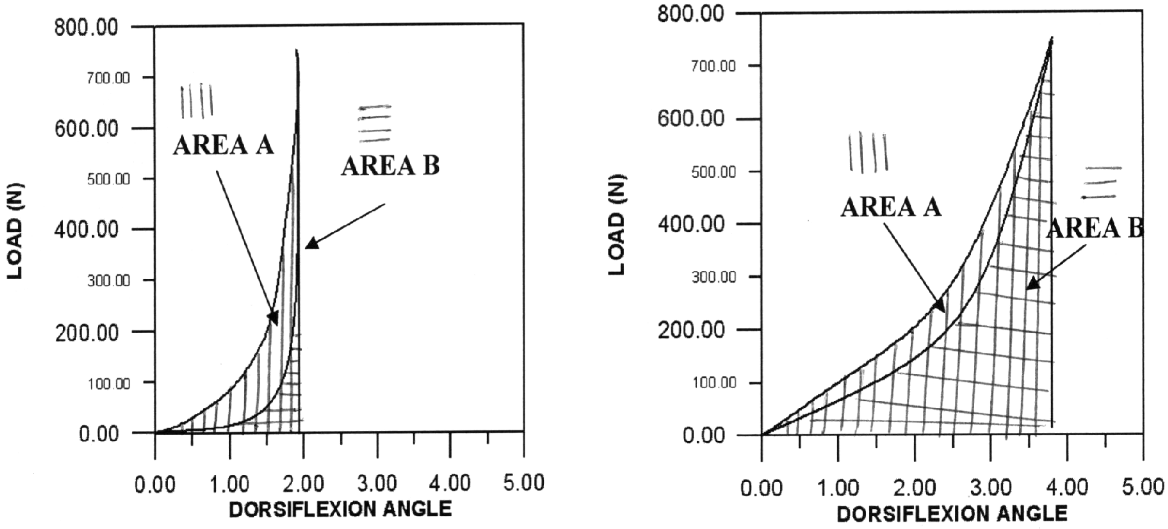


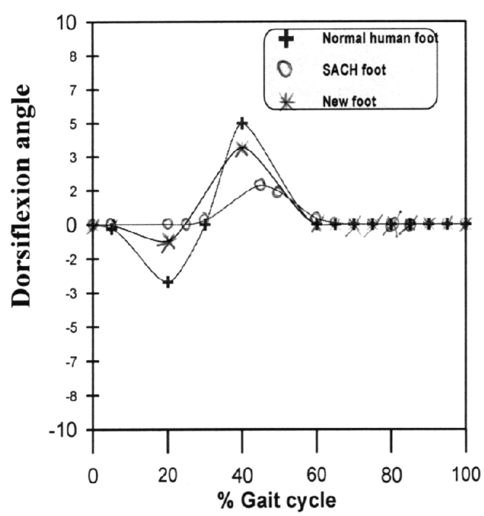
Figure (5) visual basic program to find life and failure location of new foot



FIGURE(6) LOAD WITH DORSIFLEXION ANGLE FOR : A – SACH FOOT , B- NEW FOOT



FIGURE(7) HYSTERICS LOOP FOR : A – SACH FOOT , B- NEW FOOT



FIGURE(8) DORSIFLEXION ANGLE WITH GAIT CYCLE

تصميم و تحليل قدم اصطناعي جديد للمبتورة اطرافهم

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الخلاصة :

هناك تصاميم عديدة للأقدام الاصطناعية للمبتورة أطرافهم السفلى . وغالبا ما تصنف تلك التصاميم الى نوعين منها الاقدام المحورية التحرك و الاقدام الثابتة المفصل و احدى تلك الانواع القدم الشائع الاستخدام و الذي يدعى بـ (SACH) وهو ثابت الكاحل يحتوي على و سادة في منطقة الكعب مصنعة من رغوة المطاط اما الرسخ فيصنع من الخشب الصلب و يكون قصيرا .

تعتبر استجابة المبتور طرفه من المفاتيح الاساسية في تصميم الاقدام الاصطناعية حيث من المفروض ان يشعر المريض براحة تامة في استخدام القدم من ناحية الشكل و الاداء لذا صممنا قدم جديد من مادة البولي اثلين تختلف من حيث الشكل و الخصائص عن القدم السابقة .

ان من اهم الخصائص التي يجب ان تتوفر في القدم و التي يمكن ان تضمن الحركة الطبيعة للمريض :

- مقدرة القدم على الانحناء بصورة طبيعية.
- طاقة الارجاع
- مقاومتها لفشل الكلل

في هذه الدراسة صممنا جهاز لفحص فشل القدم تحت حمل الكلل لمعرفة العمر التشيغلي لاي قدم و ذلك حسب المقياس العالمي ISO 10328 , كما قمنا بتصميم طرف اصطناعي و اجرينا عليه اختبارات مختلفة منها حساب العمر التشيغيلي, قياس زاوية الانحناء للقدم و حساب طاقة الارجاع بعد ان ابدلنا الفك السفلي لجهاز الشد و اجرينا اختبار الكلل لمادة البولي اثليين لايجاد مخطط الاجهاد – العمر , رياضيا اوجدنا صيغة جديدة لفشل الكلل في البوليمرات و من ثم تم بناء برنامج فيجوال بيسك . في النهاية اجرينا مقارنة بين خصائص القدم الجديدة و القدم السابقة (SACH) كما اجرينا مقارنة بين الجزء العملي و الجزء النظري و تبين ان القدم الجديدة كانت افضل بكل المعايير من القدم السابقة.