Design and analysis of a new prosthetic foot

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ABSTRACT

There are a large number of commercially available prosthetic feet. All prosthetic feet attempt to return some of the lost gait function, but may use different mechanical principles to do so, such as **SACH** foot (commonly), therefore, in this work, a new foot has been designed and tested. The characteristics deemed important by patients in achieving natural gait motion include: Dorsiflexion, energy return and fatigue foot test.

This study includes the design of a new prosthetic foot, fatigue foot tester according ISO 10328, measuring the ground reaction force by force plate and gait properties by testometric machine.

Finally, the new prosthetic foot has good characteristics when compared with the SACH foot , such as good dorsi-flexion (4.2^o, 1.9^o), stored energy return (58.9%, 13.14%) and life of foot (1233417and 896213)cycles .

Keyword : Prosthetic foot , Fatigue , Dorsi- flexion and Energy return .

1- INTRODUCTION:

There are different types 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. Numerous investigation have analyses compared with different types 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 should be prescribed for a particular patient. Therefore a number of studies have cycled prosthetic feet to assess their durability and wear a cyclic tester which mimics natural gait. [1]

In 1975 **Daher** [2] 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 until breakdown occurred.

Daher found that major permanent deformation and changes in resistance at the heel occurred within only 5,000 cycles.

Wevers and Durance [3] in 1987 also conducted dynamic testing on prosthetic SACH feet, but they loaded the whole trans-tibial prostheses not the foot alone. Their results were similar to **Daher's** and structural component failures of the feet at less than 100,000 cycles.

Toh et al [4] avoided the complex loading. They utilized a simple machine which did not mimic gait but applied cyclic vertical loads to the heel and forefoot only.

A report by **Kabra et al** [5] utilized a simple , low cost machine to fatigue the Jaipur foot , similar to **Toh's** device, however it appears to only simulate forefoot loading .A load-deflection analysis was also performed using a sling which passes around the foot , connects to a spring balance and reads the net acting force while the degree of movement was read from a ganiometer.

Shock absorption has been acknowledged as an important feature when used to compare different types of prosthetic feet.

Daniel Rihs and Ivan Polizzi [6] utilized the impact test. The purpose of these tests to find the shock exerted onto the residual stump of the amputee at heel strike.

Glenn K. KLute, et al [7] studied the heel region properties of prosthetic feet and shoes. To measure and model the heel in response to impact, a pendulum was constructed to mechanically simulate the conditions immediately following initial heel ground contact during walking.

A pendulum mass of 6 Kg was used to duplicate the effective mass of the stance limb at instant of heel ground reaction contact.

Francis J. Trost [8] investigated different materials that store energy when compressed by the body during early stance phase. The analysis includes measurement of the determinant of gait and oxygen consumption. Fifty two juvenile amputees were studied, the energy storing feet were provided including Flex-feet, Carbon copy feet, Seattle feet, and Sten feet.In evaluating specific activities, most amputees responded that running, jumping, climbing stairs were easier with energy storing feet.

2-THE SUGGESTED 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, preventing the fatigue failure, principle of storing energy as the stance limb accepts body weight and returns this energy as the foot lift off the ground and good dorsiflexion. There are a lot off design variable to obtain final design shape or material . This variable depends on characteristic of foot .The new foot design is to obtain optimum design by modifying the first new foot design and material selection.The shape of the new foot is dependent on dorsiflexion angle, the shock absorption and the energy return .

At heel strike the gap2 (Figure 1) is opened to allow the plantar flexion to occur as the subject achieves foot flat and begins to move over the foot. At the end of midstance the gap1 and gap2 become close and touch the top of the forefoot section. The new design foot is made of a flexible material (polyethylene).This allows the forefoot of the prosthetic foot to bend and the fatigue limit of this material is good.

3- FATIGUE IN THE NEW DESIGN FOOT BY USING PROPOSED CRITERIA

It is possible to design a simple, practical foot that achieves very specific performance criteria. The shape of new design foot is difficult to be give foot properties or to mimic normal foot in size and comfort.

$$S_f = 10^C N^b \qquad \text{…. (1a) [9]}$$

$$Log(S_f) = C + bLogN \qquad \text{…. (1b)}$$

b represents slope of equation (1b)

where N_1, N_2, S_{f1} and S_e are shown in Figure (2)

C is constant equation (1a) at N1

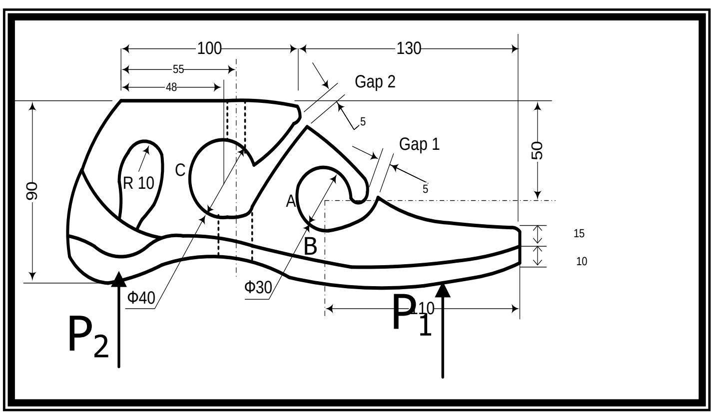


FIGURE (1) NEW FOOT DESIGN

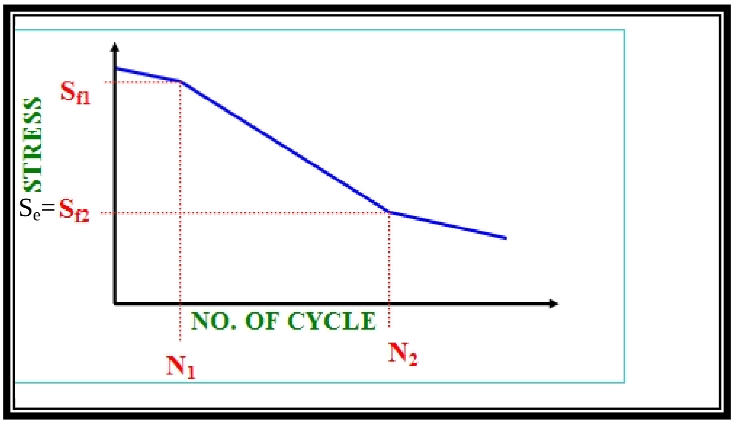


FIGURE (2) THE S-N CURVE

$$N_l = \left(\left(\frac{\sigma_a}{S_e}\right)^{LogN_1} \times \left(\frac{S_{f1}}{\sigma_a}\right)^{LogN_2} \right)^{\frac{1}{Log\left(\frac{S_{f1}}{S_e}\right)}} \qquad (2)$$

When $\boldsymbol{\sigma_a}$ is greater than endurance limit $\mathbf{S_e}$ the foot will have a finite life.

In the normal gait of prosthetic foot the load is applied at two different points at push off or called fore foot represented by point P1 in Figure (2) and at heel strike represented by point P2 in the same figure.

$$S_e = K_a K_b K_c K_d K_e K_f S'_f \qquad \text{….. (3)}$$

where K_a , K_b , K_c, K_d, K_e and K_f are factors of : surface, size , reliability , temperature , modifying stress concentration and miscellaneous respectively :

$$N_L \ at \ point \ i = \left(\left(\frac{\sigma_{ai}}{S_{ei}}\right)^{LogN_1)} \times \left(\frac{S_{f1}}{\sigma_{ai}}\right)^{LogN_2} \right)^{\frac{1}{Log\left(\frac{S_{f1}}{S_{ei}}\right)}}$$

Where i=A,B and C therefore S_{ei} : S_{eA},S_{eB} and S_{eC} are fatigue limit at A ,B and point C respectively .Comparing between N_{LA} and N_{LB} and N_{LC} then one can choose minimum number of cycles .

4- DESIGNING AND MANUFACTURING THE FATIGUE FOOT TESTER

The fatigue foot tester, Figure (3), was designed and built using the functional requirements outlined in ISO standards. According to ISO 10328 standards[10], forces must be applied at 15^o and anterior to tibia axis upon heel strike and 20 ^{o} posterior to the tibia axis upon toe off. The fatigue tester was designed to simulate human gait by alternating the heel and toe loading. The new foot and SACH foot are shown in figure (4)

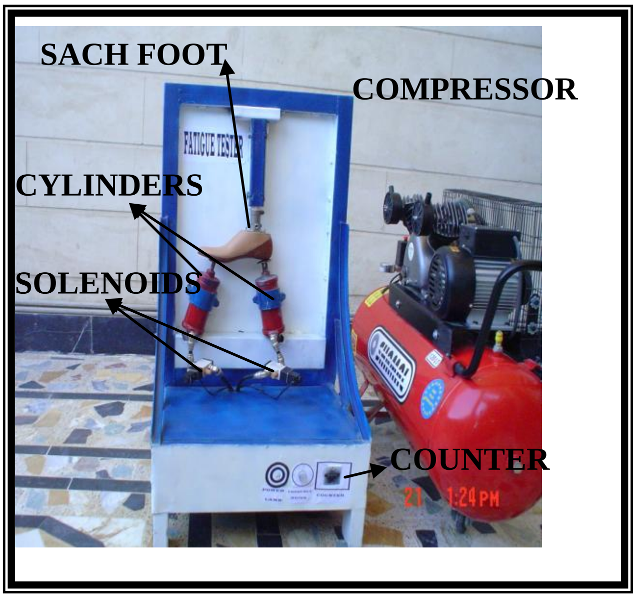


FIGURE (3) FATIGUE FOOT TESTER

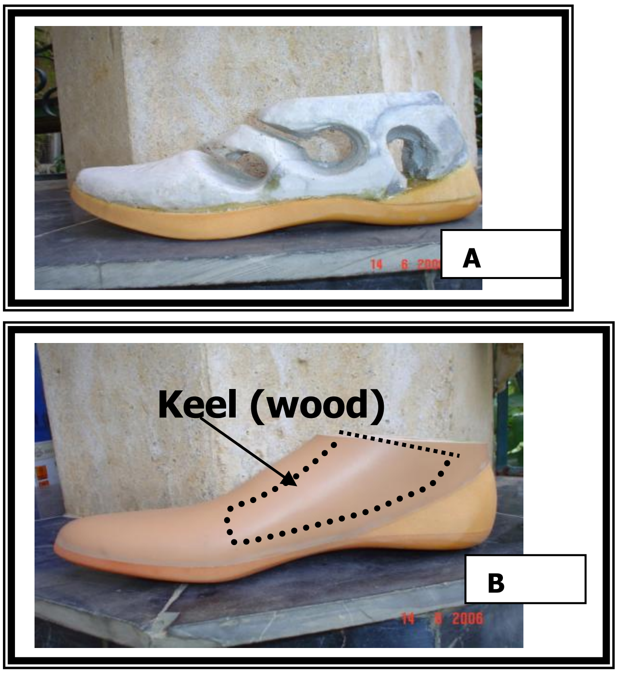


FIGURE (4)A:NEW FOOT ,B:SACH FOOTR

5-THE FOOT TESTS:

A-Fatigue foot test

The SACH foot is placed on the fatigue tester in order to obtain the life of the foot .This procedure was also applied to the new foot to compare between the two lives.

B-Dorsiflexion test:

To carry out the dorsiflexion test, a triangular piece of wood must be manufactured and supported with graded ruler,

FIGURE (5) DORSIFLEXION AND ENERGY RETURN:
A- SACH FOOT B- NEW FOOT

Figure (5).This piece of wood is put in the testometric machine. It is replaced under crosshead.

$$\varphi = \tan^{-1}\frac{Y}{X} \qquad \ldots(5)$$

C- Stored energy returned:

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

For this case, the ideal point is represented by a 743 N force and the deflection of 5^{o} dorsi-flexion which represents a 60 Kg patient with an average walking speed of (3.5 Km/h) [11].

Energy storing potential can thus be defined in the following way Figure (6)

$$Energy\ \ storing\ \ potential\ \% = \frac{Area\ \ P}{Area\ \ T}\times 100 \qquad \ldots(6)$$

Area P: Actual energy stored by material at limit.

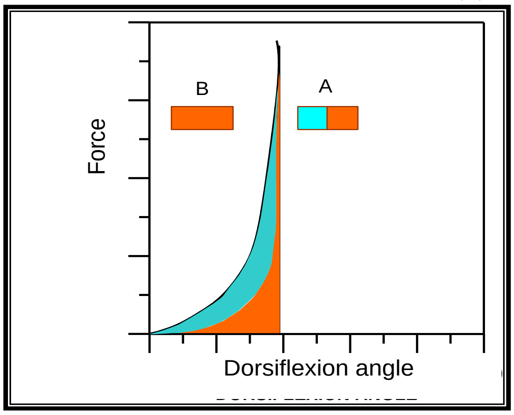
Area T: Ideal energy stored at force .

By recording the curve for loading and unloading, the hysteresis loop for the material can be determined giving a percentage of energy returned[11],Figure (6)

$$Energy\ return\ efficiency\ \% = \frac{Area\ B}{Area\ A} \times 100 \quad \ldots(7)$$

The stored energy returned is the percentage of the energy storing potential which will be returned.

$$Stored\ energy\ returned\% = Energy\ storing\ potential \times \frac{Energy\ return\ efficiency}{100} \quad \ldots(8)$$



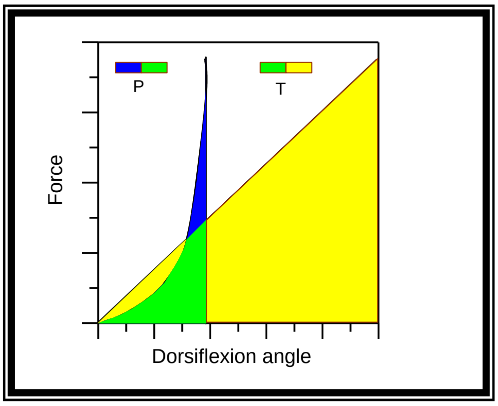


FIGURE (6) ENERGY RETURN EFFICIENCY and ENERGY STORING POTENTIAL

D- Measuring of ground reaction force :

The ground reaction force is the main force acting on the body during walking. It consists of a vertical component and two horizontal components. These forces are found by having a subject walking across a force plate in the form of walkway.

6-RESULTS:

The theoretical and experimental results are presented in this section for gait analysis the moment of ankle, dorsiflexion and ground reaction force were measured by different approaches. The new foot was designed and the number of cycle and energy return were calculated. From fatigue equations, the life of new foot was obtained, the life of new foot is 823415 cycle.The time series of computed ankle moment for the same two trials (plate for fixed)

6-1 S-N CURVE OF POLYETHYLENE:

The graph of stress range S against N is produced. Then a graph of Log S plotted against Log N and expected to be able to draw a best fit straight line from the higher to lower stress points .There will also be a horizontal line through the points at the endurance limit for polyethylene.

TABLE (1) S-N DATA FOR POLY-ETHYLEN

MATERIAL	POLYETHYLEN
S_{f1} (MPa)	19.3
S_{f2} (MPa)	4.46
N1 (CYCLE)	407
N2 (CYCLE)	3162277

6-2 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 removed from the tester at 896,213 cycles, was placed on the tester within a few months of manufacturing .

The new foot failure occurred in one specimen at 1,233,417 cycles.

TABLE (2) LIFE OF DIFFERENT FOOT

TYPE OF FOOT	LIFE OF FOOT (CYCLE)	
	THEORITI-CALLY	EXPERIMENT-ALLY
SACH (NEW)	————	896213
NEW FOOT	823415	1233417

6-3 DORSI- FLEXION AND ENERGY RETURN:

The dorsiflexion angle and eversion angle experimentally are obtained by using video (camera) then they are plotted with gait cycle. The maximum dorsiflexion angle at 65 % of gait cycle is about 5^{o} , 1.8^{o} , 4.2^{o} for normal human foot , SACH foot and new foot respectively .The stored energy returns are 13.14%, 58.9% for SACH foot and new foot respectively, Table (3)

TABLE(3) DORSI-FLEXION AND ENERGY RETURN

TYPE OF FOOT	DORSI-FLEXION ANGLE	STORED ENERGY RETURN %
SACH	1.8^{o}	13.14
NEW FOOT	4.2^{o}	58.9

6-4 GROUND REACTION FORCES AND GAIT CYCLE RESULTS:

Numerous variables can also be extracted from the force plate information. Within this investigation however, the following variables were collected:

The maximum value of the heel – strike transient, and the time at which is occurred, Figure (7). The heel – strike transient is commonly referred to as the peak, series of peaks, or noticeable change in gradient during weight acceptance of the vertical component ground reaction force.

Gait curves for each of the subject with both the **SACH** and the **new foot** were graphed. Gait curves were created for different measures of GRF angles.

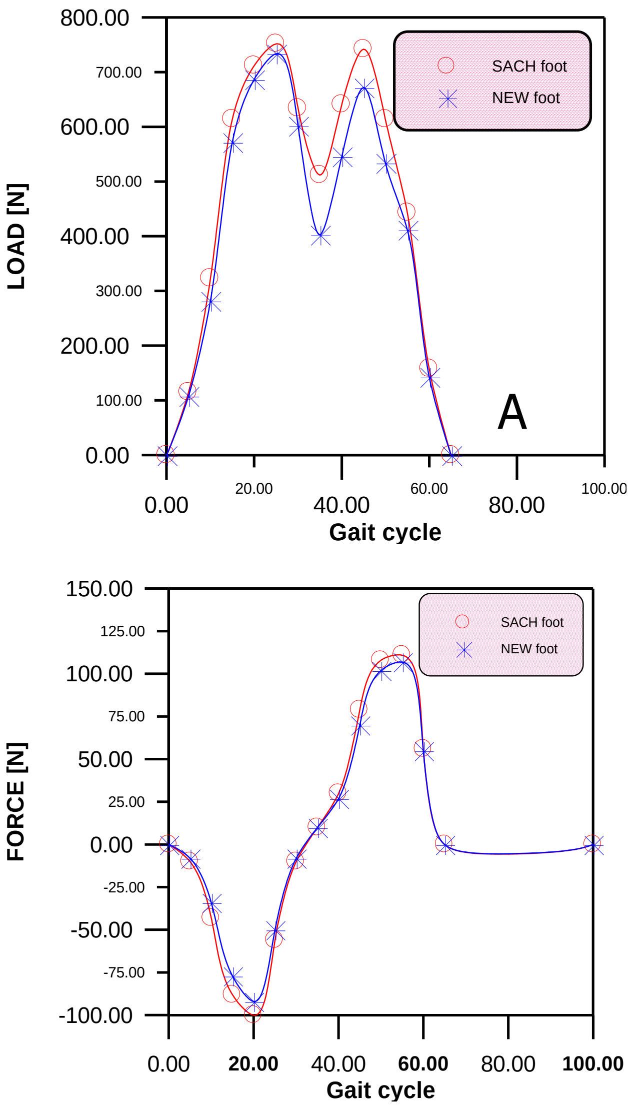


Figure (7) : A-Vertical B- Axial GRF with gait cycle

7- DISCUSSION:

The results of the amputees biomechanics gait studies reveal subtle departures from the gait pattern of the able-bodied. The flexion of the amputee is less than the mean normal amount during early stance .This occurs because the prosthetics foot does not produce the controlled plantar flexion obtained naturally by eccentric contraction of the dorsiflexiors.

During late stance , flexion is also less than mean normal values .Usually ankle motion is coordinated with foot motion ,unlike the anatomical foot , which plantarflexesion at toe-off , the prosthetic ankle cannot move when weight has been transferred to the toe section.

The current configuration of the fatigue tester is such that it applies a known force using two pneumatic cylinders , one at heel and the other at toe , to simulate walking with a prosthetic foot .The main problem with this concept is that force is not applied during the whole stepping process . But rather is applied at the two extremes of the cycle .

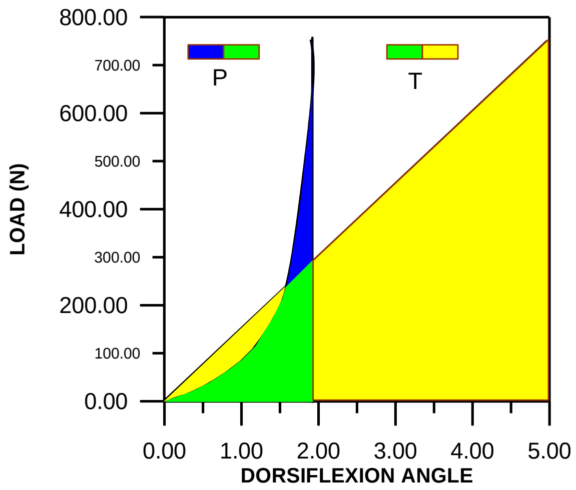
Cyclic testing is a valid method for evaluating the performance of prosthetic feet . The results obtained from the fatigue testing show that the SACH foot , old SACH and new foot design , which have a significantly stiffer heel bumper with an application force 743 N , has the ability to withstand the shearing forces placed upon the prosthetic feet at heel strike without delaminating occurring or cracks developing . It underwent the fatigue process without delaminating occurring and failure was postponed .It appears that the interface of foam / rubber of the heel bumper from distorting proximally at heel strike.

The SACH failed at the end of keel because of that the keel was manufactured from wood without dorsiflexion in the ankle, the old SACH foot failed at fewer cycles than SACH foot since the mechanical properties of polymer and rubber decrease with time .

The new foot failed at more cycles than SACH foot did because it contains two arc's ankle and keel which doubles the dorsiflexion and the material properties for polyethylene become better than rubber foam .

The stiffness and hysteresis are important properties considered in a prosthetic foot prescription. The dorsiflexion angle for SACH foot is less than for new foot because new foot contains gap at ankle and end of keel ,therefore , the energy storing potential for new foot is more than the energy storing potential for SACH foot.

The hysteresis loop for SACH foot and new foot is illustrated in Figure (9).There are different values of energy return efficiency between SACH foot and new foot. The energy return efficiency for SACH foot is less than that of new foot , therefore , the stored energy return for new foot is more than the stored energy returned for SACH foot .



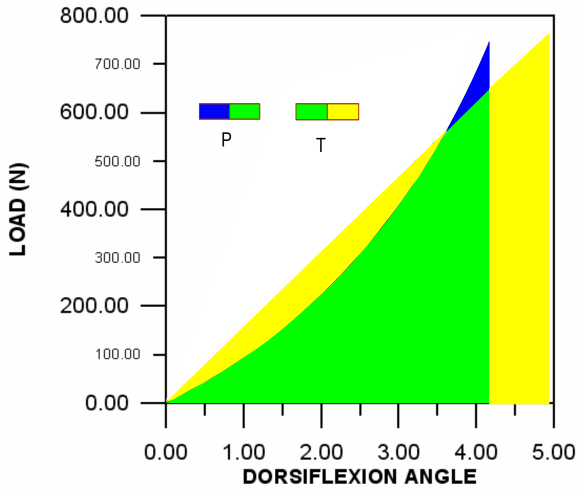
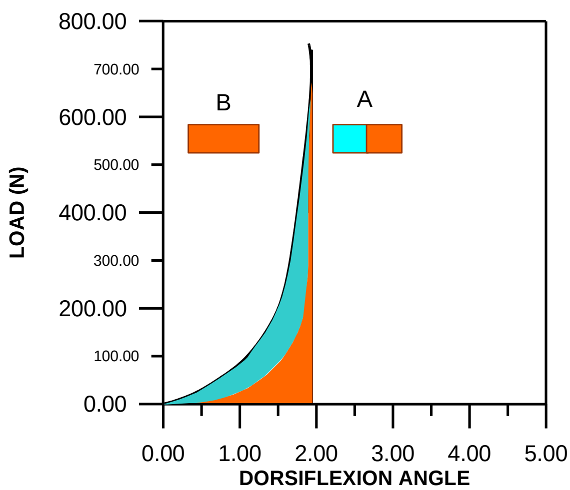


Figure (8) The energy storing potential; A-SACH foot B-new foot



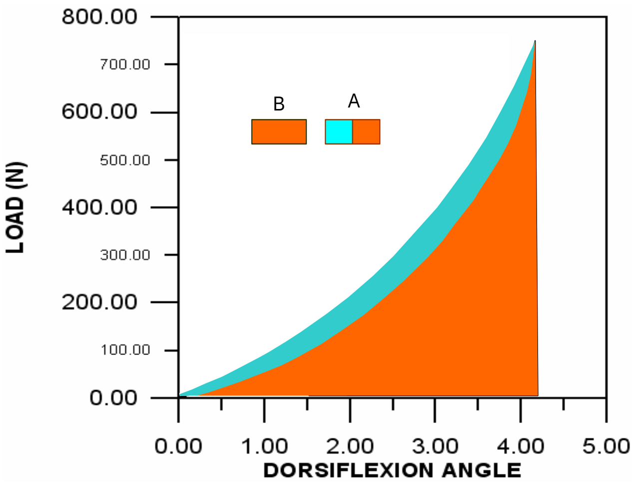


Figure (9) The energy return efficiency; A-SACH foot B-new foot

Figures (7) show the ground reaction force from force plate . The first peak is called the impact peak while the second is called the propulsion peak. The impact peak is associated with the impact of the foot. The propulsion peak is associated with the propulsion of the body forward .It has always been the main focus of the foot engineers to design the heel and ankle to reduce the impact peak while maintaining the propulsive characteristics .

Figure (7a) shows , the maximum vertical ground reaction force reaching 1.3 times of the body weight . Some of the factors affecting the magnitude of the ground reaction force are running style , running speed , footwear , ground reaction surface composition and inclination .

8-CONCLUSIONS:

The present work has reached to the following conclusions

1. The new foot is most suitable foot for the patient conditions chosen both in energy storing potential and energy return efficiency.
2. The dorsiflexion angle for the new foot are better than those of the SACH foot.
3. By comparing the characteristics exhibited by prosthetic foot to those 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 has good characteristics .
4. The vertical and axial ground reaction forces for the new foot at 40% of gait cycle is less than that in the SACH foot due to the dorsiflexion as well as the bending of the new foot at this period which is greater than the dorsiflexion for the SACH foot.
5. The new foot is better life than SACH foot.

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