Prosthetics and Orthotics International, 1993, 17, 180–188

Fatigue testing of energy storing prosthetic feet

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Abstract

This paper describes a simple approach to the fatigue testing of prosthetic feet. A fatigue testing machine for prosthetic feet was designed as part of the programme to develop an energy storing prosthetic foot (ESPF). The fatigue tester does not simulate the loading pattern on the foot during normal walking. However, cyclic vertical loads are applied to the heel and forefoot during heel-strike and toe-off respectively, for 500,000 cycles. The maximum load applied was chosen to be 1.5 times that applied by the bodyweight of the amputee and the test frequency was chosen to be 2 Hz to shorten the test duration. Four prosthetic feet were tested: two Lambda feet (a newly developed ESPF), a Kingsley SACH foot and a Proteor SACH foot. It was found that the Lambda feet have very good fatigue properties. The Kingsley SACH foot performed better than the Proteor model, with no signs of wear at the heel. The results obtained using the simple approach was found to be comparable to the results from more complex fatigue machines which simulate the load pattern during normal walking. This suggests that simple load simulating machines, which are less costly and require less maintenance, are useful substitutes in studying the fatigue properties of prosthetic feet.

Introduction

In the development of prostheses, all prosthetic assemblies and components are subjected to structural acceptance tests which include static and fatigue tests. Static tests are required to determine the structural strength of the foot to ensure performance and safety. These are carried out on a universal testing machine. While this is important, fatigue tests to reveal the fatigue strength of the components must also be performed. Fatigue tests are designed to study performance under load for the equivalent of the expected service life during normal use.

As part of the programme to develop an energy storing prosthetic foot, called the Lambda foot, a simple fatigue testing machine for prosthetic feet was designed. Fatigue testing is essential as the foot is expected to be subjected to repetitive loading during normal usage. Marsden and Montgomery (1972) conducted a survey to measure the number of steps taken by individuals during their normal activities of daily life. It was found that the number of steps taken is heavily dependent on the amount of objective walking which an individual does. A wide range in the step frequency of the individuals (in steps per hour) was recorded. It ranged from a low of 145 steps per hour for a schoolboy to a high of 1780 for a postman. Fatigue testing thus forms an integral part in the design of the prosthetic foot.

A simple approach to fatigue testing of prosthetic feet was adopted. The fatigue tester does not replicate loads acting on the foot under normal walking conditions, but a peak load equivalent to about 1.5 times that of the body weight was applied to the foot during heel-strike and toe-off. Altogether, four prosthetic feet were tested: a size 5 Lambda

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foot, a size 8 Lambda foot, a size 5 Proteor SACH foot and a size 5 Kingsley High Profile SACH foot.

The primary objective of the development of the fatigue tester was to check the fatigue strength of the Lambda foot. At the same time, it was intended to demonstrate that a simple approach to fatigue testing of prosthetic feet, which is low cost and easily reproducible, can produce comparable results obtained using more complicated machines. However, the results obtained must be treated with a certain degree of caution due to the small sample size involved. Further work is needed to obtain a more conclusive result. This paper describes the fatigue testing machine and examines the test results obtained.

The Lambda foot

The paper introduces a prosthetic foot in the class of the so called energy storing prosthetic feet, called the Lambda foot. The Lambda foot is designed to replicate the biomechanics of the normal foot-ankle assembly and to help conserve energy in amputees' ambulation. It is designed to store energy at heel strike. The energy stored during heel strike is returned to effect smooth transition from heel strike to foot flat and subsequently heel rise. From heel rise, the energy stored in the forefoot is later released in a combined forward (thrust) and upward (lift) direction which complements the gait cycle. The foot behaves like a spring where the potential energy is stored when it is loaded and the energy is returned to the system when the load is removed. This lift effect also helps to maintain the centre of gravity of the amputee at a constant level which makes locomotion less tiring.

The Lambda foot consists of a forefoot portion and a heel portion interchangeably bonded at the "ankle", which is located close to the natural ankle, by a bolt (Fig. 1). The forefoot portion extends horizontally from the ankle region anteriorly towards the toe region of the foot whereas the heel portion extends horizontally and anteriorly from the ankle region and curves downward and extends to the posterior of the foot. Both the forefoot portion and heel portion are formed by using carbon fibre laminae reinforced with a hardened, flexible epoxy polymer and are designed to serve as flat spring-like leaves so that the foot provides a strong cushioning and energy storing effect.

Fig. 1. Lateral view of the Lambda foot.

The upper portion of the ankle region defines a platform which engages the inferior aspect of a conventional prosthetic pylon. The platform is planar and is substantially rigid to sustain torsional, impact and other loads acting on the forefoot portion and the heel portion. For connecting the foot to the pylon, the ankle region has a centrally located hole through which a bolt extends and engages the threaded bore at the lower end of the pylon.

Review of fatigue testing in lower-limb prostheses

The International Society for Prosthetics and Orthotics (ISPO) (1978) recommended standards for fatigue testing of lower limb prostheses which included axial cyclic loads of 1350 N and anteroposterior (AP) cyclic bending moments about the ankle of 140 Nm. The maximum frequency for cyclic tests should be 1 Hz for assemblies containing non-metallic components and 10 Hz for assemblies of an all metallic nature. The applied load should be gradual, like a smooth sinusoidal waveform. These proposals were quite similar to those proposed by the Veteran Administration Prosthetic Centre (VAPC) during the ISPO conference, which included axial loads of 1020N and AP bending moments of 110 Nm. The VAPC (ISPO, 1978) also recommended for foot/ankle assembly, each sample should withstand 500.000 cycles under 150 lbf (667 N) load without failure and the permanent deformation should not exceed ⅛ inch (3.2 mm).

Daher (1975) published the fatigue test results of various makes of SACH feet using a fatigue tester developed in his laboratory. The prosthetic foot was loaded to simulate the loading on the foot during normal walking by air pressure cycling in pneumatic cylinders. The loading sequence was controlled by time cams. One advantage of Daher's tester is the ability to test two feet simultaneously. Wevers and Durance (1987) developed a fatigue loading machine for lower limb prostheses following the standards proposed by ISPO. The machine uses a cam drive mechanism to mimic normal gait. Both the fatigue testers represent attempts by researchers to reproduce the loading on the prosthetic foot during normal walking. Despite considerable effort, time and cost spent to design such complex machines, it is often not quite possible to reproduce all the load components acting on the foot during normal walking. It is therefore proposed that a simple approach to fatigue testing of prosthetic feet be adopted by loading the prosthetic foot using only major load components, such as the vertical force and AP bending moment about the ankle.

Design methodology

Figure 2 shows the set-up of the fatigue testing machine developed in this study. The fatigue tester is designed mainly for testing prosthetic foot/ankle assemblies. It does not simulate the loading pattern on the foot during normal walking. However, cyclic vertical loads are applied to the heel and forefoot during heel-strike and toe-off respectively. It allows the user to set a peak axial load which can be varied. Once the peak load is set, the AP bending moments about the ankle becomes dependent on the foot dimensions. The fatigue tester has no provisions for axial torsion and mediolateral bending about the ankle.

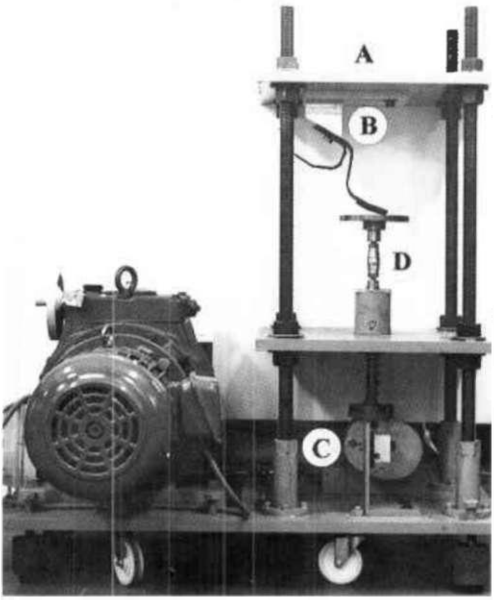


Fig. 2. Fatigue testing machine.

Components of the machine are designed for infinite life. The foot to be tested is mounted onto plate A via an ankle block B. A 30° block and a 15° block are used interchangeably for testing the forefoot and the heel respectively. The 30° block which inclines the foot at an angle of 30° to the horizontal is used for dorsiflexion and toe extension tests and the 15° block is used for plantarflexion test as recommended by the VAPC (ISPO, 1978). Cam C drives a reciprocating shaft which pushes against the foot. The required deflection on the foot to produce the desired load is pre-determined from a load deflection test conducted on the foot. Various load values can easily be obtained by adjusting the level of plate A. The maximum load acting on the foot is chosen to be equivalent to 1.5 times that of the bodyweight of the amputee. Load cell D is a Kistler Force Link 9321A and is attached to the top of the reciprocating shaft to monitor the load applied to the foot. The voltage signal from the load cell is first amplified by a Kistler miniature charge amplifier 5039A331 before it is digitised by a Keithley Metrabyte DAS-8 data acquisition card. A simple programme written in

Quickbasic stores and displays the applied load on a computer monitor.

The machine is driven by a variable speed induction motor at a frequency of 2 Hz. The loading frequency of 2 Hz is chosen over the frequency of 1 Hz adopted by Wevers and Durance (1987) to shorten the duration of the test. The Seattle foot, another energy storing prosthetic foot, was also dynamically tested at 2 Hz by Burgess *et al.* (1985). Each foot was tested to 500,000 cycles as recommended by the VAPC (ISPO, 1978). With the help of a contact relay and a timer switch, the tester can be optimised to operate approximately 80,000 cycles a day.

Test procedure

Four feet were tested: a size 5 Lambda foot, a size 8 Lambda foot, a size 5 Proteor SACH foot and a size 5 Kingsley High Profile SACH foot. Both the SACH feet had firm heel densities. In order to control the number of test parameters for the purpose of comparison, all the size 5 feet were chosen to be of about the same stiffness. However, the selection was difficult because the Lambda foot and the SACH foot are structurally different. The size 5 Lambda foot, intended for an amputee of mass 50 kg, was subsequently tested at a peak load of 736N, while the size 8 Lambda foot, intended for an amputee of mass 65 kg, was tested at a peak load of 957N. Both the SACH feet were tested at 736N to compare their durability, and ultimately their performances were compared with the Lambda feet. The feet were tested without protective footwear, as it was reported by Wevers and Durance (1987) that footwear added extra fatigue failure parameters and altered the fatigue resistance of the feet tested.

Static load deflection tests were first conducted for the heel and the forefoot portions of each foot on a Shimadzu universal testing machine, according to the standards proposed by the VAPC (ISPO, 1978). A brief description of the static tests is presented here.

The forefoot was tested by applying load to the plantar surface of each foot in the area of the toe to approximate the forces applied to the foot during the period of mid-stance to push off. The foot was placed in a dorsiflexion position at an angle of 30° to the horizontal (Fig. 3a). Vertical loads in increments of 100N were applied to the foot until a maximum of 600N was reached and the corresponding deflections were recorded.

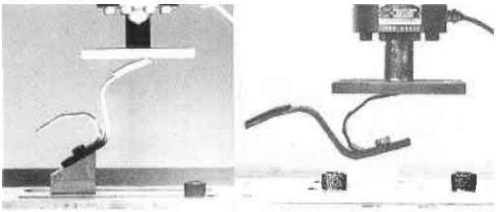

(a) (b)

Fig. 3. (a) Static test on the Lambda forefoot. (b) Static test on the Lambda heel.

The heel was tested by applying load to the apex of the heel to approximate the forces applied to the foot during the period of heel contact to foot flat. The foot was placed in a plantarflexion position at an angle of 15° to the horizontal (Fig. 3b). Vertical loads in increments of 100N were applied to the foot until a maximum of 600N was reached and the corresponding deflections were recorded.

During the static test, a "reference position", i.e. the crosshead position of the universal testing machine at the instant when the loading plate of the universal testing machine just touches the prosthetic foot, was noted. The instant when the foot just touches the loading plate was reflected by the presence of a small load value on the universal testing machine. Hereafter, this "reference position" is called the "original reference position" and the value is required in order to obtain the permanent deformation of the foot.

The foot was then transferred from the universal testing machine to the cyclic tester (Fig. 2) for cyclic testing. Cyclic tests were completed at 5,000, 10,000, 20,000, 50,000 and 100,000 cycles. Additional tests were completed at every 100,000 cycles until 500,000 cycles was reached. The above procedure was also adopted by Daher (1975). Static load deflection tests were conducted between the cyclic tests to determine if there had been any change in the mechanical properties of the foot. For each static test, a new "reference position" was also noted, which when subtracted from the "original" reference position", yielded the permanent deformation of the foot.

Results

The results of the fatigue tests of the Lambda feet and SACH feet are represented graphically in Figures 4, 5 6 and 8. The deflection-load curves at 0, 5,000 cycles and 500,000 cycles (or end of test, depending on which happened first) are plotted in each figure. It can be seen from the slope of the deflection-load curve that the stiffness of each foot increases with load. When two curves in the same figure are compared, the curve which lies below the other is said to have a higher resistance because a higher load is required to achieve the same deflection. The permanent deformations of the forefoot/heel of each foot are given in Tables 1 and 2. The permanent deformation was obtained by finding the difference between the new "reference position" after cycling and the "original reference position" before cycling.

Size 5 Lambda foot

Figure 4a shows that there is hardly any change in the forefoot resistance of the Lambda foot during cyclic testing. It is noted that the deflection-load curves at 5,000 cycles and 500,000 cycles are almost identical to the original curve at 0 cycle. Figure 4b shows the heel deflection-load curves of the Lambda foot. Like the forefoot, its resistance has not changed after the fatigue test and the deflection-load curves are almost identical before and after fatigue testing. The above observations reveal that the material and the design of the forefoot and the heel of the Lambda foot are capable of withstanding cyclic loads of up to 500,000 cycles. Table 1 shows that the permanent deformations at the end of 500,000 cycles for the forefoot and heel are 0.5 mm and 0.3 mm respectively, both values being very much lower than the permanent deformation of 3.2 mm allowed by the VAPC.

Table 1. Permanent deformation of Lambda feet.

Foot type	Size 5 Lambda foot		Size 8 Lambda foot	
Cycles completed	δ*(mm) forefoot	δ*(mm) heel	δ*(mm) forefoot	δ*(mm) heel
0	0	0	0	0
5,000	0	0.3	0.3	0
500,000	0.5	0.3	1.1	0.3

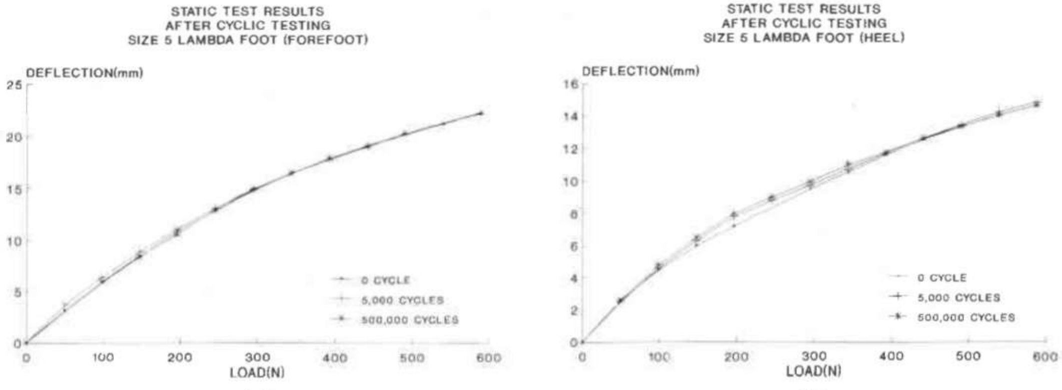
*permanent deformation

Size 8 Lambda foot

Figures 5a and b show that the deflection-load curves at 0 cycle, 5,000 cycles and 500,000 cycles are superimposed on one another, indicating minimal changes in resistance in the forefoot and heel portions after cycling. The forefoot is deformed permanently by 1.1 mm while the heel is deformed by only 0.3 mm, both values being lower than the permanent deformation of 3.2 mm allowed by the VAPC (Table 1).

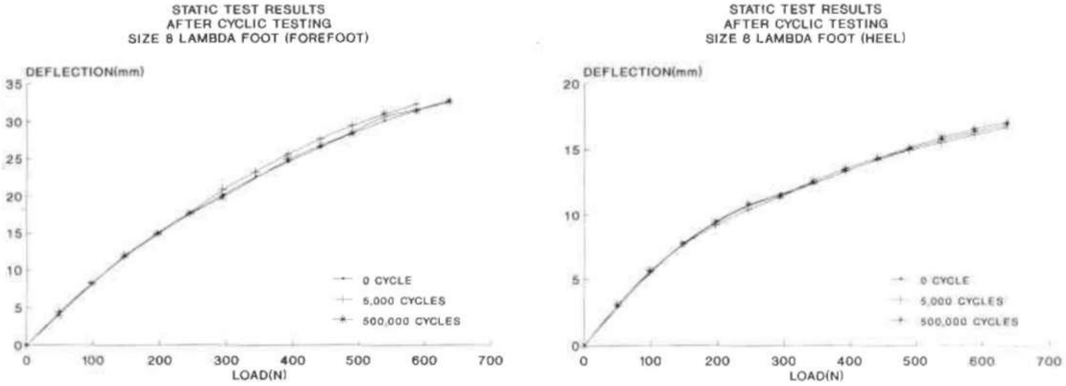
Proteor SACH foot

Figure 6a shows the changes in the forefoot resistance of the SACH foot. At the end of 5,000 cycles, the resistance of the forefoot has reduced slightly. The cyclic test was stopped at 300,000 cycles as a crack, which was visible to the naked eye, had developed in the sole of the forefoot causing a large permanent deformation of 13 mm (Table 2). It is noted that the resistance of the forefoot has increased at the



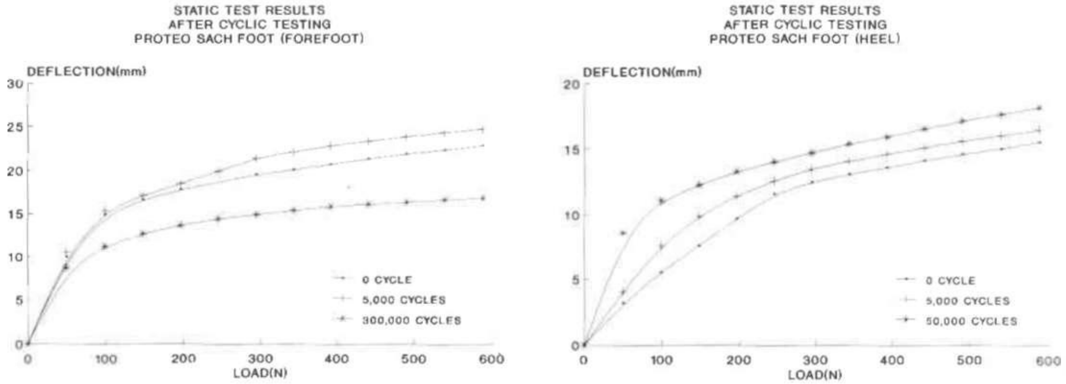
(a) (b)

Fig. 4. (a) Forefoot resistance of size 5 Lambda foot. (b) Heel resistance of size 5 Lambda foot.



(a) (b)

Fig. 5. (a) Forefoot resistance of size 8 Lambda foot. (b) Heel resistance of size 8 Lambda foot.



(a) (b)

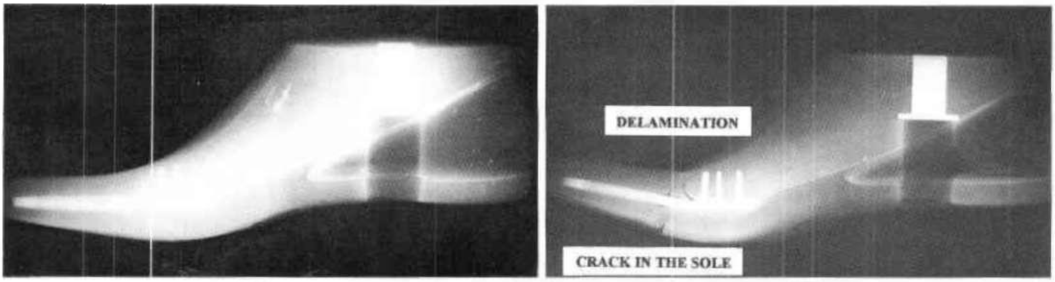
Fig. 6. (a) Forefoot resistance of Proteor SACH foot. (b) Heel resistance of Proteor SACH foot.

Table 2. Permanent deformation of SACH feet.

Foot type	Size 5 Proteor SACH foot		Size 5 Kingsley SACH foot		Size 5 Lambda foot	
Cycles completed	δ (mm) forefoot	δ (mm) heel	δ (mm) forefoot	δ (mm) heel	δ (mm) forefoot	δ (mm) heel
0	0	0	0	0	0	0
5,000	0.4	0.8	1.0	0.3	0	0.3
500,000	13.3*	3.1⁺	8.0#	0.7	0.5	0.3

*test discontinued at 300,000 cycles ⁺test discontinued at 50,000 cycles #test discontinued at 400,000 cycles.

end of the test (the reason is discussed later in the paper). Figure 6b shows that there is a reduction in heel resistance at the end of 5,000 cycles. It was observed that the wedge sponge-like material at the heel began to wear at 10,000 cycles. The cyclic test was stopped at 50,000 cycles due to the breakdown of the heel. Figures 7a and b are photographic reproductions of the X-ray lateral views prior to and subsequent to the testing respectively. Figure 7b shows the wear of the wedge sponge-like material at the heel. The stiffener attached to the wooden keel was deformed which explains the large permanent deformation of 13 mm for the forefoot. Further, the foam at the region where the stiffener is joined to the keel



(a) (b)

Fig. 7. (a) X-ray lateral view of Proteor SACH foot before cycling. (b) X-ray lateral view of Proteor SACH foot after cycling.

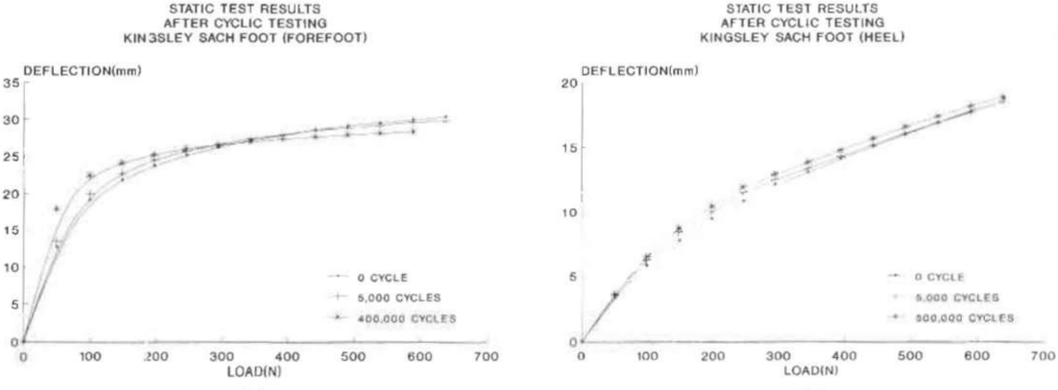
exhibited cracks and delamination from the keel.

Kingsley SACH foot

Figure 8a shows that the forefoot resistance of the Kingsley SACH foot has reduced slightly at the end of 5,000 cycles as also observed in the Proteor SACH foot. The test was stopped at 400,000 cycles as a crack had developed in the sole of the forefoot. Very interesting behaviour during the testing of the SACH foot is reflected in the deflection-load curve at the end of 400,000 cycles. The resistance of the forefoot has increased. Referring back to Figure 6a, the Proteor foot also exhibited similar behaviour, but its increase in resistance is more than the Kingsley foot due to its larger permanent deformation. The reason for the above is that once the foot has been deformed permanently, the wooden keel of the SACH foot makes a greater contribution thereby increasing the resistance considerably. A permanent deformation of 8 mm was recorded for the Kingsley forefoot (refer to Table 2). However, the heel of the Kingsley SACH foot is very durable. Figure 8b shows that the resistance varied very little during the testing and no visible wear on the heel wedge was observed. A permanent deformation of 0.7 mm was recorded for the heel.

Discussion

It was mentioned earlier that the machines designed by Daher (1975) and Wevers and Durance (1987) simulate loading on the prosthetic foot during normal stride by including various forces and moments. It is interesting to compare the results obtained by both researchers with the results obtained from the simple approach adopted here. However, the comparison is not absolute because the test parameters are not completely identical. Daher tested the prosthetic feet with shoes and the average peak load was 981N. The main objective of Wevers' experiment was to evaluate the fatigue strength of prosthetic



(a) (b)

Fig. 8. (a) Forefoot resistance of Kingsley SACH foot. (b) Heel resistance of Kingsley SACH foot.

sockets and the recommended peak load of 1350 N was used. Further, the prosthetic feet may not be of the same sizes. Nevertheless, it is useful to compare the results.

The Kingsley High Profile SACH foot in Daher's test was deformed permanently by 8.9 mm and 3.8 mm for the forefoot and the heel respectively at the end of 500,000 cycles. From Table 2, the Kingsley SACH foot tested here was deformed by 8.0 mm and 0.7 mm for the forefoot and the heel respectively. Both the results are comparable and it is believed that the larger values in Daher's test is because of the higher loads used. The fact that the sole of the SACH foot in Daher's test did not show any cracks at the end of the test could be because the foot was tested with shoes. Daher also mentioned that the heel of the Kingsley SACH foot is very resilient. No internal physical breakdown was observed by X-ray in both cases. It was seen earlier that the forefoot deflection-load curves for both the Proteor and Kingsley SACH feet show an initial reduction in resistance at the end of 5,000 cycles, but the resistence increased at the end of the test. This was because once the foot was deformed permanently, the wooden keel of the foot would be stressed. Similar observations were observed in almost all the deflection-load curves for the forefeet in Daher's work, but the phenomenon was not reported.

Wevers reported that the Kingsley SACH foot failed at 105,800 cycles. The fatigue life was shorter than that obtained by the simple approach because of the higher load used by Wevers. All the SACH feet [US Manufacturing, Otto Bock (German Winnipeg) and Kingsley] showed cracks in the soles at the end of the test.

The above discussion shows that the results obtained from the simple approach are consistent with the results obtained from the more complicated machines. It is also noted that a Proteor foot worn by an amputee over a period of six months shows similar wear at the sole and heel to the one that was dynamically tested.

It is felt that the axial load of 1350 N proposed by ISPO for lower limb prostheses is too high for the SACH foot. All the SACH feet tested by Wevers at such a high load failed prematurely. Although, the SACH feet tested by the simple approach were subjected to loads smaller than 1350 N, the feet failed before 500,000 cycles. It is also felt that the load value is designed more for Caucasians as Asians generally have lower body mass. Such high loads are normally experienced by active amputees during sport activities but are only occasionally experienced by less active amputees during unforeseen events like stumbling over obstacles. However, the cyclic load of 667 N proposed by the VAPC for foot/ankle assemblies may be too low. With the proliferation of ESPF, amputees will be motivated to engage in sport activities and the loads experienced will be higher. Prosthetic feet tested at such low loads would not be reliable. A compromise between the recommended loads of 1350 N and 667 N would be ideal. So far, publications relating to ESPF only mentioned the feet have been dynamically tested, but no details of such tests have been given.

The simplicity in the design of the fatigue tester is its main advantage. This results in lower cost and less maintenance requirement. A further advantage is that the peak load is easily reproducible and can be varied easily. However, the present design does not allow the forefoot and the heel to be tested together. This will increase the duration of the test. In Daher's and Wevers' design, because the foot is taken through the complete walking cycle, both the forefoot and the heel are tested simultaneously.

Although the results obtained by the simple approach are comparable to that obtained using more complex machines, it is cautioned that the results obtained are not conclusive because of the small sample size. It is recommended that further work using the simple approach be carried out using more specimens.

Conclusion

The fatigue tester has been used successfully to study the durability of the Lambda feet and the SACH feet. It was found that the Lambda feet have very good fatigue properties as the deflection-load curves at the beginning and at the end of the cyclic test were almost identical and the maximum permanent deformation for both the Lambda feet was 1.1 mm which was below the 3.2 mm allowed by the VAPC. However, the cyclic test on the Proteor SACH foot was hampered by the wear and breakdown of the rubber sole and sponge heel, which caused the test to be terminated prematurely.

The forefoot of the Kingsley SACH foot performed better than the Proteor model but also broke down prematurely. However, the heel of the Kingsley model was very durable with no wear at all. The results obtained were also found to be comparable to the results obtained using more complex fatigue testers.

Acknoweledgements

The authors gratefully acknowledge the financial assistance of a research grant (RP900327) from the National University of Singapore and the technical assistance of Singapore Aerospace Manufacturing Pte. Ltd. for fabricating the Lambda feet.

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