Prosthetics and Orthotics International, 1984, 8, 147–154

Biomechanical evaluation of SACH and uniaxial feet

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Abstract

A review of prosthetic prescription practice reveals that in the United Kingdom about 85% of below and above-knee amputees are fitted with uniaxial feet, whereas in the United States about 80% are fitted with SACH feet. An evaluation method was developed to assess the performance of these two different types of feet. This included a subjective assessment procedure and a biomechanical evaluation of the function of the two feet and their effects on whole body gait kinematics and lower limb kinetics.

Data were acquired by three Bolex H16 cine cameras and two Kistler force plates. This set-up allowed three-dimensional analysis on the prosthetic and contralateral sides of the subject. Investigations were undertaken in which an experimental prosthesis permitted the interchange of the ankle/foot while keeping the rest of the components the same. Altogether, six below knee and five above knee amputees were tested. No clear trend for preference for either type of foot was evident from the subjective survey; in general the patients showed a preference for the foot that they were accustomed to. Kinematic and kinetic analysis showed some differences in the function between the two prosthetic feet. It is the purpose of this paper to discuss these differences and their significance.

Introduction

Many prosthetic feet and ankle mechanisms have been designed to date, some incorporating ingenious mechanisms capable of imitating functions and movements of the normal foot and ankle complex (Wagner and Catranis, 1954). However, the complexity of most of these designs, their excessive maintenance requirements and unacceptably high mass have prevented their wide use. The two most common prosthetic feet used nowadays are the uniaxial (single-axis) type and the solid ankle cushion heel (SACH) foot.

The uniaxial foot in its present form originated in 1861, when J. E. Hanger (U.S.A.) replaced the cords in the "American Leg" by rubber bumpers about the ankle joint (American Academy of Orthopaedic Surgeons 1960). Since then, the device has undergone many modifications. However, its basic principle of operation still remains the same. There is an articulating ankle joint with a horizontal shaft located in plain bushes or ball bearings. Two bumpers (one in front and the other at the rear of the axis) provide the restraining and restoring moments about the ankle joint for plantar and dorsiflexion movements, simulating the normal foot and ankle flexion function during level walking.

The SACH foot was developed at the University of California, Berkeley, in the early 1950's. (Radcliffe and Foort, 1961). It consists of a wedge of cushioning material built into the heel and an internal keel, shaped at the ball of the foot to provide a smooth rolling action. The heel wedge cushions the impact at heel strike and compresses to give the effect, albeit limited, of plantar flexion. The foot has no articulating ankle joint thus eliminating the need for maintenance of moving mechanical parts.

Prescription criteria for prosthetic feet have been derived from experience gained by the clinician and prosthetist. Over the years several studies have been conducted to supply statisical data on prescription patterns of prosthetic components, notably: Litt and Nattress (1961), Davies et al (1970) and Fishman et al (1975), in the United States. In the United Kingdom, the Department of Health and Social Security (DHSS) has published annual statistics for England, Wales and Northern Ireland since 1957.

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Table 1. Prescription patterns for prosthetic feet.

	U.S.A. (Fishman et al. 1975)		U.K. (D.H.S.S., 1976)	
Ankle/foot components	B/K	A/K	B/K	A/K
Uniaxial	15%	23%	89%	79%
SACH	81%	74%	1%	2%
Others	4%	3%	10%	19%

A review of the above studies reveals that the most common prosthetic foot prescribed in North America for above and below-knee amputees during the 1970s was the SACH foot. On the contrary, in the United Kingdom the most common prosthetic foot prescribed was the uniaxial foot (Table 1) while the SACH foot was rarely prescribed. Recent statistics, however, indicate a slight increase in its usage (DHSS, 1980).

Review of published work

In 1955, New York University was contracted by the Veterans Administration to determine the performance of the SACH foot against that of the single axis (with toe-break type) wooden foot. (Fishman et al, 1955). Three below-knee and three above-knee "active" unilateral amputees participated in the programme. A high level of acceptance of the SACH foot was indicated in the clinical analysis. The engineering evaluation using force plate data showed that the above-knee amputees had a smoother transition from heel to toe with the SACH foot. This effect was not detected in the below-knee amputees. Following on in the 1960s, clinical experience in North America indicated a high preference for the SACH foot. (Gordon and Ardizzone, 1960; Wilson, 1962).

In the United Kingdom, there was no report of studies carried out to indicate the high preference for the uniaxial foot, although it had been suggested by experienced prosthetists that better knee stability could be achieved with the uniaxial foot during early stance.

Recently a study by Doane and Holt (1983) on the comparison of the SACH and single-axis foot in the gait of eight unilateral below-knee amputees was carried out. They found no significant difference in most of the kinematic data of the lower extremity and the temporal parameters during gait. The only significant difference was in the ankle angle at the beginning of the foot flat period where the single-axis foot displayed a plantar flexion angle 6.5° greater than that of the SACH foot. They concluded that the interchanging of the two prosthetic feet in a prosthesis does not affect the gait pattern of the amputees.

Subjects and materials

Surveys of amputation levels show that over 80% of the population are either below-knee or above-knee (Table 2). This is true for the United States as well as the United Kingdom. These two groups of amputees are the main users of prosthetic feet and were therefore considered in this evaluation programme. Altogether six below-knee and five above-knee male unilateral amputees were selected to participate in the trials. The average age of the below-knee and above-knee amputees was 53 (standard deviation SD=9) and 48 (SD=11) respectively.

To quantify the activity level of each amputee, the assessment method proposed by Day (1981) was used. The average score for the below-knee amputees was 33, while that for the above-knee amputees was 37. These values represented an active group of amputees.

In order to minimize the variables which might influence the results, it was necessary to provide each amputee with an experimental prosthesis, which was sufficiently adaptable to accommodate either the SACH or uniaxial foot. The Otto Bock modular system was found to be suitable for this purpose. All the below-knee amputees were fitted with a standard PTB with suprapatellar cuff suspension prosthesis, while all the above-knee amputees were fitted with a quadrilateral (total contact) suction socket and a single-axis knee mechanism prosthesis. Each prosthesis was provided with an additional shank tube to accommodate the height

Table 2. Distribution by level of amputation.

	U.S.A.				U.K.			
Amputation level	Glattly, 1964		Kay & Newman, 1975		D.H.S.S., 1976		D.H.S.S., 1980	
Upper extremity	14.5%		8.3%		5.4%		4.3%	
Above-knee	44.1	80.9%	32.6	86.4%	52.7	84.1%	51.7	87.4%
Below-knee	36.8		53.8		31.4		35.7	
Other lower extremity	4.6%		5.3%		10.5%		8.3%	

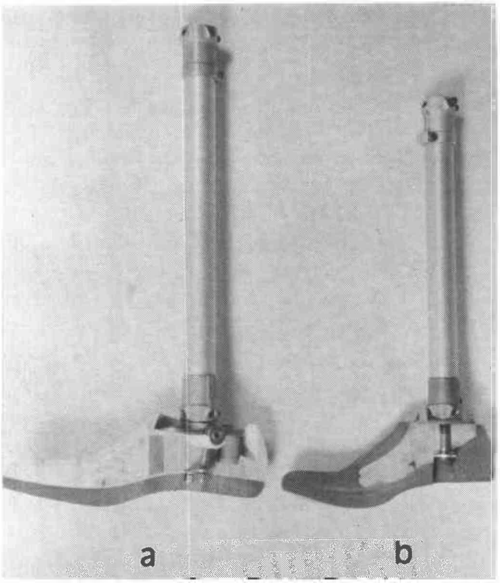


Fig. 1. Prosthetic feet evaluated (a) Uniaxial foot (b) SACH foot.

discrepancy between the SACH and uniaxial feet. Figure 1 shows the Otto Bock SACH and uniaxial feet used in this study.

Gait measuring system

The laboratory consisted of a walkpath approximately 20 metres long. Two Kistler force plates and three Paillard Bolex H-16 cine cameras were arranged as shown in Figure 2. This arrangement allowed three-dimensional analysis of both sides of the human body.

Each camera was driven by a synchronous motor at mains frequency (i.e. 50 Hz) through a gear ratio of 8: 1. The internal gear ratio of the camera is 1: 8, therefore a shutter frequency of 50 cycles/s was achieved. The sampling rate for the force plate signals was also set at 50 Hz. A PDP/12 mini computer was used to store data from both force plates. The three cine cameras and two force plates were synchronized during the walking trials by a single external event.

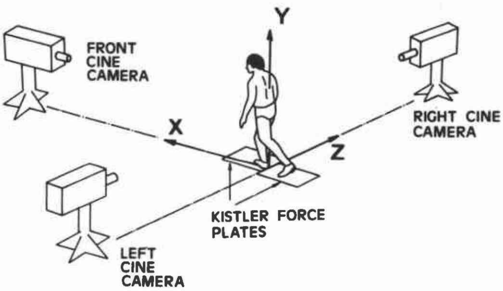
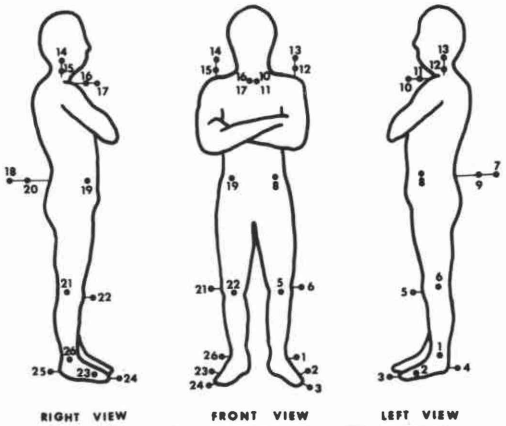


Fig. 2. Gait measuring system.

Methodology

Dynamic alignment of the experimental prosthesis (either with SACH or uniaxial foot) was performed by an experienced prosthetist prior to the walking trials. This involved rotating and tilting of the various prosthetic components, and selecting the most suitable density of heel wedge for the SACH foot or the plantar rubber bumper for the uniaxial foot. When the "optimum" alignment was achieved, the amputee was allowed to become accustomed to the prosthesis. Meanwhile, the prosthetist recorded a final assessment of the amputee's gait on a given form.

Lightweight, spherical (10 mm diameter) body markers were positioned and taped on to the anatomical landmarks (Fig. 3). The



Marker Numbers And Their Locations		
Right	Definition	Left
14	Acromion Process 1	13
15	Acromion Process 2	12
16	Sternum 2	11
17	Sternum 1	10
18	Pelvic Tail 1	7
19	Anterior Superior Illiac Spine	8
20	Pelvic Tail 2	9
21	Fibula Head	6
22	Tibial Tuberosity	5
25	Mid - Heel / Calcaneus	4
24	2nd Toetip	3
23	5th Metarsar Base	2
26	Lateral Malleolus	1

Fig. 3. Locations of body markers.

amputee was then instructed to walk along the walkpath towards the front camera. Five successful runs were recorded; successful meaning when contact was made with the two force plates, with the left foot on one and the right foot on the other. The amputee and the prosthetist were then asked to comment on the performance of the prosthetic foot, in respect of: function, cosmesis, comfort and effects of the foot on other components in the prosthesis.

The procedure was repeated after interchanging the prosthetic foot and shank tube. After the walking trials, the amputee and the prosthetist were asked to comment on the overall performance of each foot.

The alignment of the prosthesis was measured and the mass and mass moment of inertia were determined. Both prosthetic feet were also subjected to static tests on a tensile testing machine, according to the Veteran's Administration standard (Veterans Administration Prosthetics Center, 1973).

Data reduction

The cine films were processed and the positions of markers digitized for transfer to an ICL 1904S mainframe computer for analysis. The force plate data were sorted on the PDP/12 and subsequently also transferred to the ICL 1904S.

A suite of programs, written in Fortran, was used in the analysis of both the cine and force plate data. Initial data processing included calibration, parallax correction and digital filtering of raw displacement data. Further processing gave the three-dimensional kinematic data of the whole body as well as the forces and moments at the hip, knee and ankle of the prosthetic and contralateral limbs.

Results and discussion

The plantar rubber bumper supplied with the Otto Bock modular uniaxial foot (moulded-type) was too soft for most of the amputees. Consequently, plantar rubber bumpers of four different stiffnesses had to be specially moulded in the Bioengineering Unit. These allowed the selection of bumpers that were most acceptable to the amputees and prosthetists.

The proposed guide for the selection of the heel stiffness of the SACH foot by Radcliffe and Foort (1961) was found to be inadequate. For example, the medium grade SACH foot was preferred even by amputees whose body weight exceeded that recommended. Furthermore the guide does not make provision for amputees who require a soft grade SACH foot. A revised guide should be established in which the basis of selection of heel stiffness should not only include the level of amputation and body weight but also the level of activity of the amputee. There is no existing guide for the selection of rubber bumper stiffness for the uniaxial foot.

The Veterans Administration standard appears to be valid for the SACH feet only (Veterans Administration Prosthetics Center, 1973). It was observed that for a particular amputee, the heel stiffness preferred for the uniaxial foot was always more stiff than that of the preferred SACH foot according to the load versus deformation curve (Fig. 4). This is due to the different load bearing characteristic of the SACH and uniaxial foot. It is suggested that a standard be compiled for the articulating ankle joint type of prosthetic foot, in which the ankle moment versus angluar displacement is used as a means of classification.

The subjective assessment showed that of the six below-knee amputees tested, three preferred the uniaxial foot, two preferred the SACH foot and one had no specific preference. Of the five above-knee amputees, three preferred the uniaxial foot while the remaining two preferred the SACH foot. No clear trend of preference for

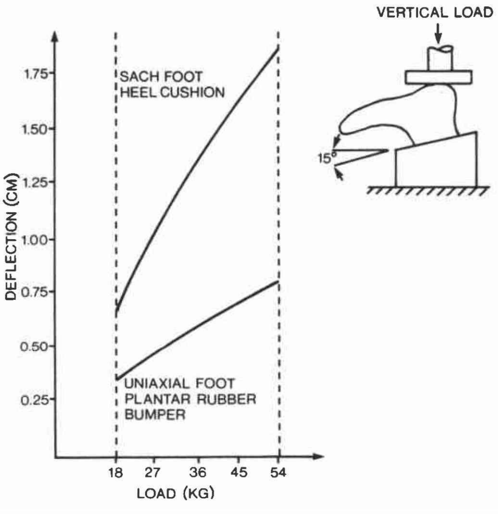


Fig. 4. Static plantar flexion testing. From VA Standards and Specifications for Prosthetic Foot/ Ankle Assemblies (1973).

Table 3. Subjective assessment of amputee's preference.

Amputation level	Amputee	Amputee's own prosthesis	Overall preference
Below-knee amputees	BR002	SACH	SACH
	BR003	SACH	SACH
	BL004	Uniaxial (wooden)	Uniaxial (moulded)
	BR005	SACH	Uniaxial (moulded)
	BR007	Uniaxial (wooden)	No preference
	BL012	Uniaxial (moulded)	Uniaxial (moulded)
Above-knee amputees	AR001	SACH	SACH
	AL006	Uniaxial (moulded)	Uniaxial (moulded)
	AR010	Uniaxial (wooden)	Uniaxial (moulded)
	AR011	Uniaxial (wooden)	Uniaxial (moulded)
	AL013	SACH	SACH

either type of foot was evident. In general the amputees showed a preference for the foot to which they were accustomed (Table 3).

When the prosthetic foot and shank tube were interchanged it was necessary to re-align the prosthesis. The difference in alignment was due to the height discrepancy of approximately 1.5 cm and the antero-posterior difference in attachment point of the foot bolt relative to the heel of the foot of approximately 1.5 cm. Furthermore, the heel stiffness of the prosthetic foot also influences the alignment of the prosthesis. Therefore in this evaluation, alignment of the prosthesis had to be considered as an integral part of the fitting of the respective foot. The alignment of the prosthesis, whether with the SACH or uniaxial foot, was found to be within the "optimum" alignment range established with the SACH foot in an on-going project in the Bioengineering Unit. No differences in gait were observed by the prosthetist resulting from the difference in alignment of the prosthesis with SACH and uniaxial foot.

Table 4 shows the averaged temporal parameters of the below-knee amputees. A two sample, two-tailed t-test at 5% level was used to determine whether the means were significantly different. The averaged preferred speed of walking was found to be the same whether the SACH or uniaxial foot was used. The stance phase of the sound limb is longer than that of the prosthetic side and consequently the swing of the sound limb is shorter than that of the prosthetic side. This is consistent with the findings reported by Molen et al (1973) and Breakey (1976). The percentage of the walking cycle occupied by stance phase however, for both the sound and prosthetic sides was shorter than that reported. This could be due to the faster speed of walking. The difference in prosthetic stance phase for the SACH and uniaxial foot was found to be insignificant.

The most significant difference was found in the temporal components of the prosthetic stance phase (Table 4). The uniaxial foot demonstrated similar characteristics to the normal foot. This is because the compression of the rear bumper controls the foot plantar flexion about the hinge joint, in a similar manner to the pre-tibial muscles in the normal subject. With the SACH foot, the period of heel-strike to foot-flat took twice as long as that of the normal foot; the rigid ankle prevents pivoting about the ankle axis. Consequently, foot flat position has to occur by compression of the heel cushion and forward movement of the knee joint. These

Table 4. Temporal parameters of below-knee amputees. Percentage of stance phase.

Temporal components of stance phase	Normal subjects	Below-knee amputees: Contralateral side, SACH foot	Contralateral side, Uniaxial foot	Prosthetic side, SACH foot	Prosthetic side, Uniaxial foot
Heel-strike to foot-flat	17.9%	19.6%	21.1%	44.5%	22.4%
Foot-flat to heel-rise	55.2%	53.6%	50.0%	15.9%	44.0%
Heel-rise to toe-off	26.9%	26.8%	28.9%	39.6%	33.6%

	Normal	SACH foot	Uniaxial foot
Speed of walking (m/s)	1,465 (±0.085)	1,354 (±0.139)	1,360 (±0.095)

Table 5. Temporal parameters of above-knee amputees. Percentage of stance phase.

Temporal components of stance phase	Normal subjects	Above-knee amputees			
		Contralateral side		Prosthetic side	
		SACH foot	Uniaxial foot	SACH foot	Uniaxial foot
Heel-strike to foot-flat	17.9%	18.8%	18.1%	33.7%	20.4%
Foot-flat to heel-rise	55.2%	51.6%	53.5%	15.6%	36.5%
Heel-rise to toe-off	26.9%	29.6%	28.4%	50.7%	43.1%

	Normal	SACH foot	Uniaxial foot
Speed of walking (m/s)	1,465 (±0.085)	1,043 (±0.062)	1,043 (±0.062)

patterns were also evident in the above-knee amputees (Table 5).

The average speed of walking for the above-knee amputees was the same whether the SACH or uniaxial foot was used. This value is slightly higher than that reported by Murray et al (1980). No other significant differences in the temporal parameters were evident between the SACH and uniaxial foot.

In order to assess the smoothness and aesthetic quality of gait, the trajectories of the joint centres of the lower limb and shoulders were examined. It was thought that the hip and shoulder trajectories might provide useful evaluation criteria. However, comparison of the trajectories obtained with SACH and uniaxial feet showed no significant differences. This was true for both the below-knee and the above-knee amputees.

The ankle angle was found to be significantly different between the SACH and uniaxial foot during early stance phase i.e. the plantar flexion angle of the foot. Doane and Holt (1983) also reported this difference in below-knee amputees. The below and above-knee amputees showed an average difference of 7.5° and 5° respectively. The uniaxial foot in this respect functions in a manner closer to the normal foot than does the SACH foot. Those amputees who preferred the uniaxial foot expressed a liking for this plantar flexion action. One below-knee amputee commented that the uniaxial foot was "much more lively and natural". The average knee flexion angle was also found to be slightly greater during the stance phase for the uniaxial foot. However the difference was insignificant.

The ground reaction forces for below-knee amputees did not show any significant difference in magnitude or pattern when comparison was made between SACH and uniaxial feet, although, as expected, differences between the prosthetic and sound limbs were evident. From the force vector diagrams, shown in Figure 5 (top), the uniaxial foot displayed a slightly more rapid forward change in its point of force application during the mid-stance period than the SACH foot. This occurred during the transitional phase, when the plantar flexion bumper was relieved and initial loading of the dorsiflexion stop took place. The active below-knee amputees were able to use their intact knee to control this event to minimize any abrupt change in load action that might otherwise have occurred. Thus, the forces and moments at the hip, knee and ankle of the prosthetic and contralateral limbs showed no significant difference, whether the prosthesis incorporated the SACH or the uniaxial foot.

The vertical ground reaction force on the prosthetic side for the above-knee amputee showed differences in its loading pattern between the SACH and uniaxial foot. Figure 5, (bottom) shows the typical force vector diagrams. The SACH foot has a two peak loading pattern although the span of forces applied over the second peak is extended. This reflects the rocker-shaped design of the wooden keel in the SACH foot and also the inability of the prosthetic knee to control this event, whereby the amputee rolls over the ball of the foot with the prosthetic knee locked. The smooth "roll-over" can be characterized by the fairly constant forward change in the point of force application.

The uniaxial foot displayed a three-peak loading pattern. The second peak is the result of the rapid forward change of the point of force application during the transitional phase already mentioned above. The prosthetic limb is unable to control this phase well; this causes a rapid increase in the upward acceleration of the body.

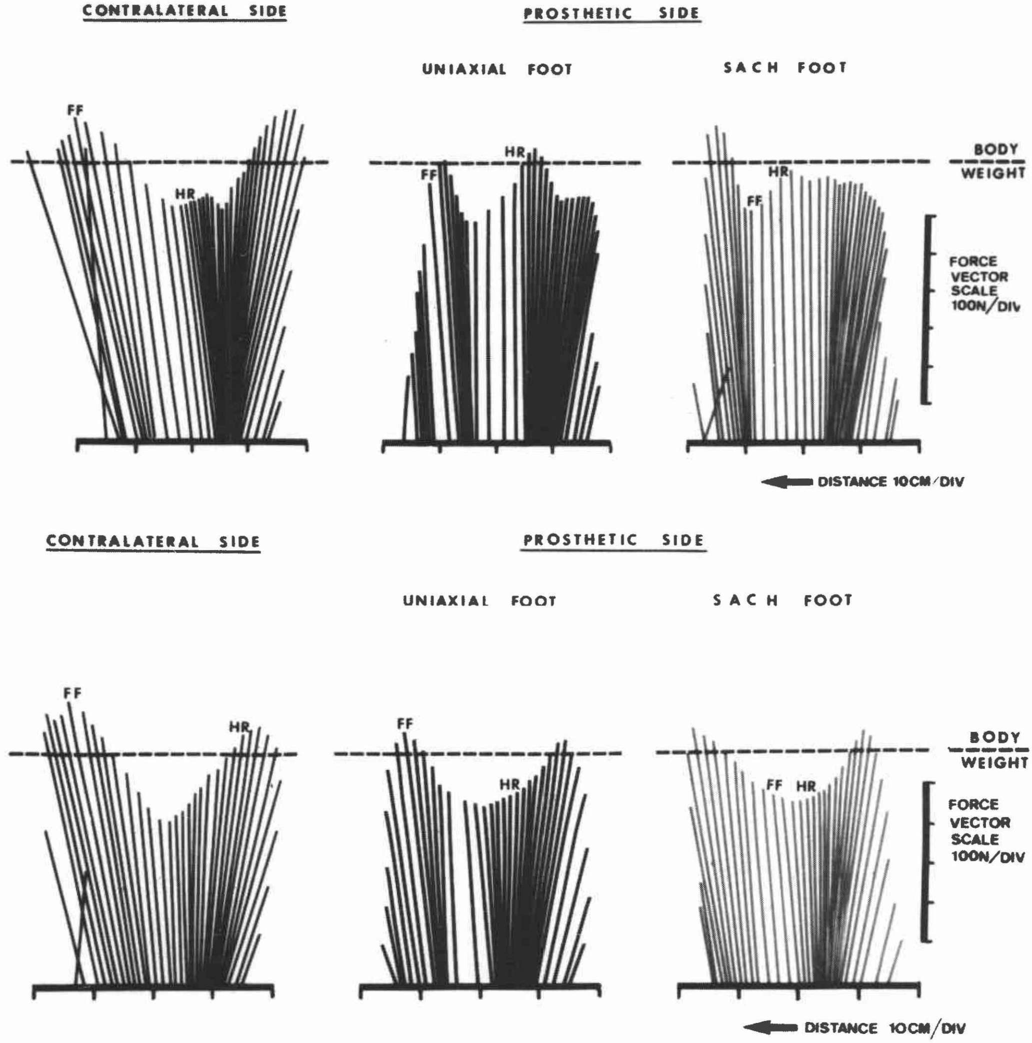


Fig. 5. Top, typical force vector diagrams of below-knee amputee. Bottom, typical force vector diagrams of above-knee amputee.

The third peak represents the initiation of toe-off. The design of the distal section of the uniaxial foot could also have influenced the smoothness of the "roll-over".

These differences in the ground to foot loading pattern and smoothness of "roll-over" obtained between the two designs of feet for above knee amputees were also reported by Fishman et al (1955). Apparently, however, these differences were compensated for by the amputees so that the moments at the hip, knee and ankle showed no significant difference.

Conclusions

Subjective assessment presented no clear trend of preference for either type of prosthetic foot. In general, the amputees showed a preference for the foot to which they were accustomed.

The kinematic analysis showed that considering foot action alone, the uniaxial foot resembles more closely the normal foot in providing plantar flexion in early stance. On the other hand, examination of the ground force actions showed that the SACH foot gives a smoother transition from heel-strike to toe-off. These differences nevertheless did not produce any significant differences in the whole body kinetics.

It can be concluded that with proper selection of heel stiffness and alignment of the prosthesis, both types of prosthetic feet can be made to function so that similar whole body kinetic patterns can be obtained. In this respect, if costs and maintenance requirements are included as factors in prosthetic foot selection, then the SACH foot would be the first choice for the unilateral active below and above-knee amputees.

Amputees, who are "inactive" (i.e. geriatric or enfeebled), might benefit from having early foot flat to provide better support and stability. In this case, the uniaxial foot might be a better choice.

Acknowledgement

This work is part of a PhD thesis submitted to the University of Strathclyde (Goh, 1982). The authors wish to acknowledge the support of a Strathclyde Open Postgraduate Studentship Award throughout this study.

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