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A biomechanical comparison of the SACH, Seattle and Jaipur feet using ground reaction forces

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Abstract

The Jaipur prosthetic foot was developed in India in response to specific socio-cultural needs of Indian amputees. It is being used extensively in India and several other developing countries. Its claim of being a cheaper and satisfactory alternative to other prosthetic feet has not been investigated biomechanically. The present study was undertaken to compare its biomechanical properties with the SACH and Seattle feet, using ground reaction forces.

Three trans-tibial amputees participated in the experiment which measured the ground reaction force data using a Kistler force plate. Subject's normal foot was used as a reference. Six variables from the vertical and anteroposterior components of ground reaction forces were quantified. their statistical analysis showed that the normal foot generates significantly larger ground reaction forces than the prosthetic foot. The shock absorption capacity of the SACH foot was found to be better when compared with the other two feet, while the Jaipur foot allowed a more natural gait and was closer in performance to the normal foot. None of the prostheses significantly influenced the locomotor style of the amputees.

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Introduction

The last decade has seen many technological and material developments in the field of lower limb prosthetics. This includes a greater understanding of biomechanics, extensive use of CAD CAM techniques and the availability of new and composite materials. Expectations of amputees have also increased in terms of a greater desire to participate in recreational and sporting activities. these advances have led to the evolution of several new designs of ankle-foot assembly. The most exciting amongst these are the so called "energy storing prosthetic feet" (ESPF), of which the Seattle foot is the most popular example. In spite of the increasing popularity of these new designs they have hardly dented the dominance of the SACH foot which due to its unique properties, is used throughout the world.

Another significant development which has largely gone unnoticed is the evolution of the Jaipur foot from India. It is widely used there and in several other developing and under-developed countries. It has not been recognized in the developed world presumably due to a lack of awareness and the absence of its biomechanical evaluation. There is also a popular impression that it is meant for barefoot walking, although amputees do use it satisfactorily with shoes.

The Jaipur foot came into existence in response to socio-economic and cultural needs (of squatting, cross-legged sitting and barefoot walking) of Indian amputees. It consists of three

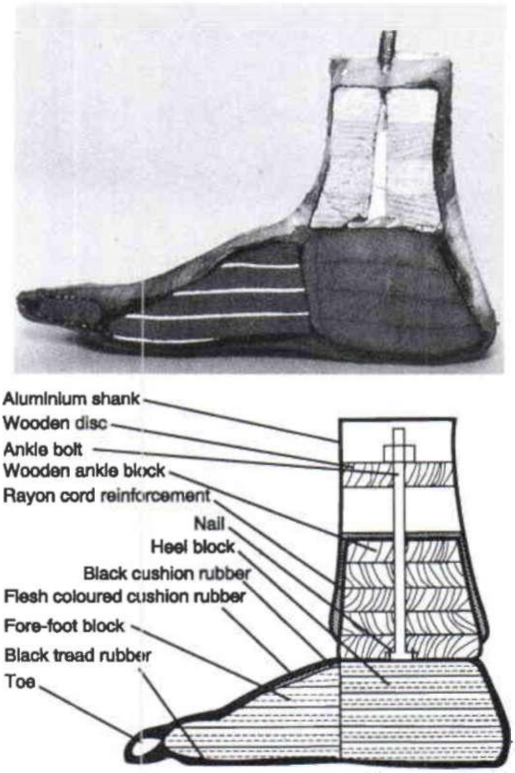

Fig. 1. A sagittal section of the Jaipur foot.

structural blocks simulating the anatomy of a normal foot (Fig. 1). The forefoot and heel blocks are made of sponge rubber while the ankle block is made of light wood. The three components are bound together, enclosed in a rubber shell and vulcanized in a die to give it the shape and cosmetic appearance of a real foot (Sethi, 1978 and 1988). It is probably one of the cheapest commercially available prosthetic feet. Although a very durable, waterproof and supple foot, it is heavier than most other prosthetic feet. Its production is labour intensive and the cosmesis and standardization still remains far from satisfactory. Currently it is being used in India and six other developing countries. In India alone more than 200,000 amputees have been fitted with it to date (Sethi, 1993).

There are numerous reports in the literature which evaluate the different prosthetic feet (Edelstein, 1984; Goh *et al.,* 1984; Wagner *et al.*, 1987; Michael, 1987; Murray, 1988; Torburn *et al.,* 1990; Mizuno *et al.,* 1992) but only one previous report in English literature (North *et al.,* 1974) has investigated some of the biomechanical properties of the Jaipur foot. They used a strain gauged pylon dynamometer to measure the axial load, torque, medio-lateral and antero-posterior moments of the lower limb joints. They were unable to reach any definite conclusions regarding differences between the Jaipur and SACH feet, and observed that more patient tests would be required to investigate any significant differences in the variables measured.

The main function of an ankle-foot prosthesis is to facilitate locomotion. The biomechanical assessment of locomotion is traditionally done by evaluating its kinematic and kinetic characteristics. The later criteria are more useful as, by using a force plate to measure ground reaction forces, characteristics of shock absorption and locomotor style can be studied (Lees and Bouracier, 1994).

The magnitude and rate of vertical ground reaction forces indicates the shock absorption capacity of the foot. Some of the other variables of ground reaction forces such as braking impulse, support impulse, propulsive impulse and force can help in assessing the gait style. These, respectively, indicate the efforts put into initial contact, support and propulsion into the next stride. Thus, a comparison of shock absorption capacity and locomotor style by measuring ground reaction forces, can be used to judge the performance of different prosthetic feet.

The present study was undertaken to assess the performance characteristics of the Jaipur foot by comparing its shock absorption capacity and influence on gait style with that of SACH and Seattle feet, using the ground reaction forces. These three feet were selected for comparison as they not only belong to the same group of non-articulated ankle-foot assemblies but also represent the most widely used designs of prosthetics feet in general.

Material and methods

Subjects

Three healthy adult males with left trans-tibial amputations were selected for the study from the Donald Tod Rehabilitation Centre, Fazakerley Hospital, Liverpool. Their age range was 43-47 years and their weight ranged from 66 to 86kg. All three were established, fairly active and gainfully employed amputees. All the subjects normally wore an *Endolite PTB prosthesis with a soft prosthetic liner and †Quantum foot as a terminal device. Each subject gave informed consent before participating in the experiment.

Prostheses

Three experimental prostheses were used. While the SACH and Seattle feet were obtained locally, the Jaipur foot was specially procured from Jaipur (India). In order to minimize the variables which might influence the results, it was necessary to provide each amputee with an experimental limb, adaptable to accommodate each of the three prosthetic feet. This was a replica of their usual prostheses but with a provision in the lower end of the shin tube to interchange the foot by loosening and tightening a screw. An alignment device was fitted at the socket/shin tube junction and the alignment checked by a qualified prosthetist.

Procedure

The experiment was conducted using a Kistler force plate (type 5281B). The three co-ordinate force data were sampled at a rate of 200Hz. Using each prosthesis in turn, subjects walked at a self selected speed over the force platform. Fifteen trials were recorded for walking and the subject was required to repeat a similar number of trials at a jogging pace. No attempt was made to force a fixed speed. The exact speed, however, was recorded using a timing gate so as to exclude the readings with excessive speed variations (+/- 10% of SRH selected speed) and to ensure consistency of speed on repeat visits. One subject was unable to complete the trials involving jogging as he did not feel comfortable during this. The subject's normal foot was used as a control reference and all wore their usual prosthesis with a Quantum foot during control trials. A total of three test sessions were conducted for each subject on three different days.

Data processing

From the fifteen successful trials recorded for each condition, the ten best were selected for analysis by visual inspection, omitting data which appeared atypical. Six variables were quantified from the ground reaction forces. These were the impact force peak, impact loading rate, propulsion force peak, and the vertical impulse obtained from the vertical ground reaction force; and the negative (braking) and positive (propulsive) impulses from the horizontal ground reaction forces. The data were normalised to body weight before being analysed. Analysis was done using an ANOVA model, and a level of statistical significance of $p<0.01$ was used unless otherwise stated.

Result

Typical force curves for walking and jogging are shown in Figures 2 and 3 respectively. These curves show the vertical and antero-posterior force components. The curve for walking is typified by three distinct peaks. The first, referred to as the impact force peak, is small but sharp and is associated with heel strike. The second, referred to as the loading force peak, is larger and more rounded and corresponds to loading of the foot just before mid-stance. The third, referred to as the propulsion force peak, is associated with the push-off into the next stride. The area under the vertical force curve gives a measure of the support impulse, while a combination of the magnitude of the impact force peak and the time taken to reach it gives the impact load rate. The antero-posterior force is typified by an initial braking phase followed by a propulsive phase. The corresponding areas under each part yield the braking and propulsive impulses respectively.

The curve for jogging contains similar characteristics, except that the loading and propulsive force peaks are now combined to give just one discernible peak which is referred to as drive-off force peak, to indicate a more dynamic action and to distinguish it from the two separate peaks identified in the walking data.

Amongst these six variables the impact force peak and the impact load rate are considered as representing the shock absorption characteristics, while the propulsive (and drive-off) force peak and the support impulse represent a walking (or jogging) style. In addition the braking and propulsive impulses are also considered to represent gait style.

Three test sessions were conducted to

*Trade name of Blatchford modular, carbon fibre endo-skeletal construction.

†Trade name of the Vessa "energy storing foot."

Table 1. Mean (N=10) heel strike force peak (N/kg body mass) for walking (Three sessions being shown as S_1, S_2, S_3)

		PROSTHESIS			
		SACH	SEATTLE	JAIPUR	NORMAL FOOT
Subject 1	S1	1.39	1.75	2.60	5.29
	S2	1.64	2.47	2.84	4.97
	S3	1.81	1.62	2.79	5.53
Subject 2	S1	1.18	1.88	2.50	7.27
	S2	1.33	1.70	2.32	6.40
	S3	1.32	1.67	2.31	6.67
Subject 3	S1	0.91	1.04	1.67	4.22
	S2	1.25	1.28	1.63	3.84
	S3	0.94	1.16	1.56	3.46

Table 2. Mean (N=10) propulsive force peak (N/kg body mass) for walking (Three sessions being shown as S_1, S_2, S_3)

		PROSTHESIS			
		SACH	SEATTLE	JAIPUR	NORMAL FOOT
Subject 1	S1	9.80	9.63	9.85	11.18
	S2	9.78	9.47	9.70	11.19
	S3	9.96	10.02	9.89	11.09
Subject 2	S1	9.51	9.66	9.67	10.52
	S2	9.75	9.73	9.41	11.61
	S3	9.30	9.56	9.12	10.78
Subject 3	S1	9.80	9.99	9.91	11.35
	S2	10.06	10.03	9.74	11.43
	S3	9.84	9.82	9.79	11.07

overcome the possibility of a movement pattern fixation noted for athlete response testing for sport footwear (Lees and Bouracier, 1994). It has been found that subjects may produce consistent but untypical movement patterns due to the testing environment. Repeated trials mitigate against this, ensuring that data collected are a true representation of an individual's gait style. Mean data for selected variables over each test session are given in Tables 1 and 2. It can be seen from this that there are marked differences between test sessions for a particular subject/prosthesis combination, indicating that there is a session effect. There is no trend in the session effect (e.g. as a result of habituation to the testing protocols) and so for further analysis, and to reduce the effect of movement pattern fixations, the data from each session were combined.

The combined data for the two shock absorption variables and the four gait style variables are presented in Table 3 for each prosthetic foot and for the normal foot. Levels of statistical significance derived from the

Table 3. Mean data averaged over each test session and all subjects for walking. Fz refers to the vertical force while Fy refers to the horizontal force.

	PROSTHESIS				NORMAL FOOT	
	SACH	SEATTLE	JAIPUR			
Shock absorption				p		p
Fz Impact force peak	1.29	1.62	2.25	<.001	5.30	<.001
Fz Impact load rate	96.8	136.8	190.3	<.001	329.6	<.001
Gait style						
Fz Propulsive force peak	9.76	9.76	9.67	NS	11.13	<.001
Fz Support impulse	5.85	5.93	5.79	NS	6.57	<.01
Fy Braking impulse	0.288	0.283	0.317	<.001	0.388	<.001
Fy Propulsive impulse	0.273	0.278	0.274	NS	0.361	<.001

UNITS: force (N/kg); load rate (N/s.kg); impulse (N.s/kg)

Table 4. Mean (N=10) heel strike force peak N/kg body mass) for jogging (Three sessions being shown as S_1, S_2, S_3)

PROSTHESIS					
		SACH	SEATTLE	JAIPUR	NORMAL FOOT
Subject 1	S1	4.06	4.34	3.89	13.93
	S2	3.55	3.67	3.98	14.55
	S3	2.33	3.31	3.80	14.20
Subject 2	S1	3.45	3.31	3.56	12.44
	S2	1.98	3.46	3.49	12.40
	S3	2.19	3.19	3.38	10.51

Table 5. Mean (N=10) drive off force peak (N/kg body mass) for jogging (Three sessions being shown as S_1, S_2, S_3)

PROSTHESIS					
		SACH	SEATTLE	JAIPUR	NORMAL FOOT
Subject 1	S1	12.88	14.22	14.35	20.13
	S2	14.46	14.72	14.01	20.14
	S3	13.74	13.62	15.68	20.39
Subject 2	S1	16.85	17.51	18.39	21.03
	S2	15.71	15.94	17.11	19.68
	S3	15.69	15.77	17.04	20.24

ANOVA model are given for a comparison firstly between the three prosthetic feet and secondly, between the normal foot and all prosthetic feet. It can be seen that the normal foot yields significantly different results than the prosthetic feet in all variables. In particular, the normal foot shows a higher impact force peak and impact load rate, indicating a more severe contact with the ground. This is confirmed by a larger braking impulse. The larger support impulse for the normal foot as compared to the prosthetic foot indicates an asymmetry in gait with more weight being put on the normal foot. The asymmetry is continued into the propulsive phase with a larger propulsive force peak and a greater propulsive impulse.

Table 3 also indicates that there are significant differences amongst the prosthetic feet. These differences are mainly in the shock absorption variables. The Jaipur foot shows the greatest impact force and impact load rate while the SACH foot shows the lowest values in these variables. There is also a significant difference between the three feet in the braking impulse with the Jaipur foot again having the largest values. The differences in other variables are insignificant.

Tables 4 and 5 give data for each session for jogging. One subject was unwilling to jog, so data was available from only two subjects. It can be seen that similarly there are differences between sessions confirming the session effect noted above for walking. The data for each session were combined to form a total mean value for each prosthesis and the normal foot

Table 6. Mean data averaged over each test session and both subjects for jogging. Fz refers to the vertical force while Fy refers to the horizontal force.

	PROSTHESIS				NORMAL FOOT	
	SACH	SEATTLE	JAIPUR			
Shock absorption				p		p
Fz Impact force peak	2.93	3.55	3.69	NS	13.0	<.001
Fz Impact load rate	241	320	314	NS	335	NS
Gait style						
Fz Propulsive force peak	14.9	15.3	16.1	NS	20.2	<.01
Fz Support impulse	2.96	3.11	2.97	NS	4.03	<.001
Fy Braking impulse	0.136	0.148	0.135	NS	0.195	<.001
Fy Propulsive impulse	0.134	0.111	0.043	<.001	0.160	<.001

UNITS: force (N/kg); load rate (N/s. kg); impulse (N.s/kg) which is presented in Table 6. Here it can be seen that, in general, there is only a small difference between each prosthesis, but a highly significant difference between the prosthetic and the normal foot.

Discussion

Several different variables such as joint angle and moments, stride time and energy consumption in walking have been used in the past to compare the performance of different prosthetic feet. Shock absorption characteristics of prosthetic feet have not been widely studied. Effective shock absorption at the ankle-foot complex is a desirable feature of any prosthetic foot as it protects the lower limb joints, by reducing the amount of forces transmitted proximally (Radin *et al.,* 1972; Volyshin and Wosk, 1982; Van Leeuwen *et al.,* 1990).

In a normal foot, there are in-built mechanisms to absorb shock and dampen the ground reaction forces (such as subtalar joint movements and heel pad compression) but in an amputee, the prosthetic foot has to substitute for those lost functions.

It is possible to evaluate the shock absorption capacities of prosthetic feet as well as their effect on gait style by analysing ground reaction forces.

Significantly lower values of all parameters in all prosthetic feet compared to normal (Table 3) suggests that significantly less ground reaction forces are generated on the amputated side, possibly because of structural and functional loss following amputation. In other words, amputees land more softly on the prosthetic foot probably because they feel less secure with an artificial limb as compared to the normal leg and therefore, load it cautiously. The increased stresses on the normal side results in an asymmetrical gait, which is consistent with previous observations that at best a normal gait in an amputee can be described as asymmetrical, having below normal acceleration and deceleration on the prosthetic side (Van Leeuwen *et al.,* 1990).

It has been recently observed that the discrepancy of weight bearing in amputees can be reduced by bio-feedback training (Quinlivan, 1994).

A notable feature in the vertical ground reaction force data is the initial peak identified here as the heel strike or impact force peak. There is surprisingly very little information in the literature about it and none about its magnitude. Murray *et al.* (1988), found it only

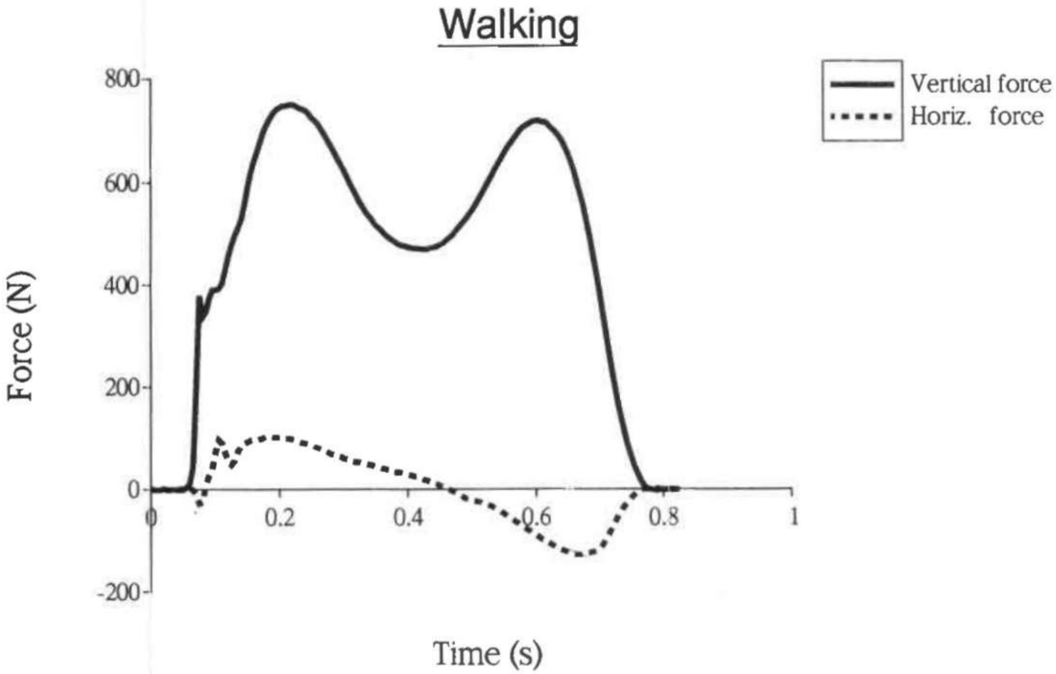

Fig. 2. A typical ground reaction force curve for walking.

on the prosthetic side. The authors found this peak consistently in both prosthetic and normal feet during walking and jogging (Figs. 2 and 3).

The impact peak and its slope represents the magnitude and rate of generation of vertical ground reaction forces. A small impact force peak and lower impact load rate would imply that more ground reaction forces are being absorbed at foot level, hence the better shock absorption capacity of the prosthesis, assuming that all the feet are being loaded equally. In the study, the SACH foot produced the smallest forces, apparently indicating its better shock absorption capacity compared to the Seattle and Jaipur feet. Findings were consistent in all subjects irrespective of walking pattern or velocity. Previous reports are not unanimous on this issue. Murray *et al.* (1988) found the shock absorption quality of the Seattle foot better than the SACH foot, while Torburn (1990) did not find any significant difference between the SACH and the Seattle feet. It should be noted that these authors used the force peak referred to in this study as the loading force peak. This is distinct from the impact force peak used here to determine the characteristics of shock absorption.

The antero-posterior braking impulse represents the force of loading. In the Jaipur foot it was significantly larger and nearer to the value obtained from the normal foot. This implies that amputees loaded it more, probably because they felt more secure and confident with the Jaipur foot. This would seem to suggest that the performance of the Jaipur foot is more natural and nearer to normal than the other two feet. This is entirely possible because it has been primarily designed for barefoot walking. A further study involving data collection from the normal foot with each of the three prosthetic feet on the amputated side would be more informative.

The propulsive force peak represents the push-off force of the foot as it drives off into the next stride. The greater push-off capacity of the energy storing prosthetic feet has often been claimed because of a larger propulsive force peak (Murray *et al.*, 1988). However, opinions vary on this issue. According to Perry (1974), this peak is actually a result of leverage of body alignment or the locomotor style rather than representing the magnitude of propulsive forces. Wagner *et al.* (1987) also supports the idea that it is primarily a product of alignment. They, as well as Torburn *et al.* (1990) and Amann (1990) have all shown that there is no significant

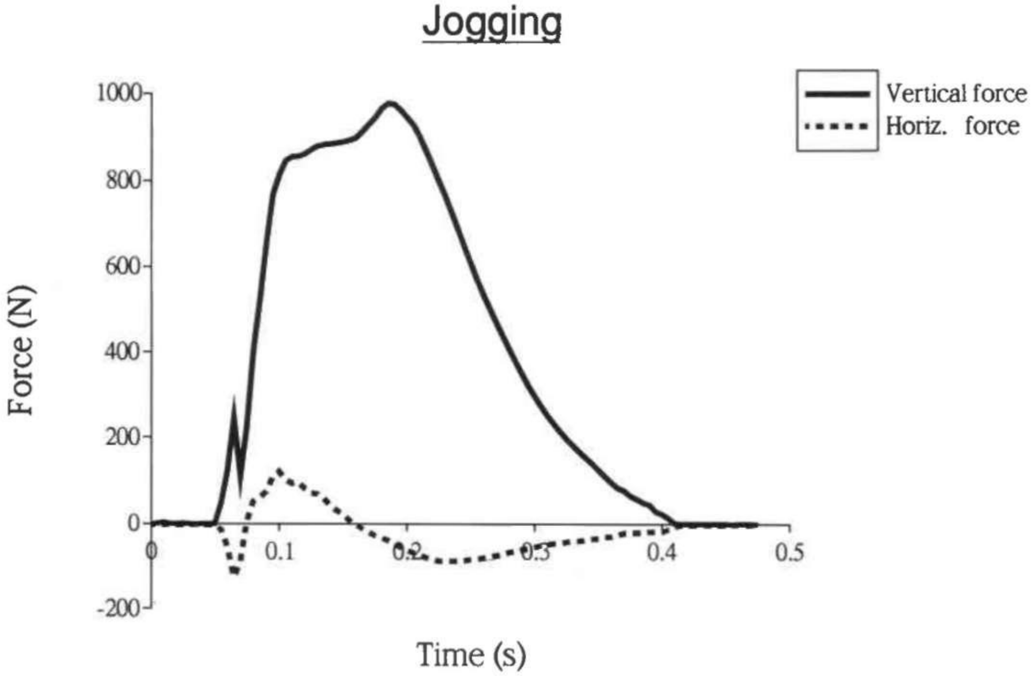

Fig. 3. A typical ground reaction force curve for jogging.

difference in the magnitude of late ground reaction force between different prosthetic feet. The results of this study support this theory. No significant difference was found in the magnitude of the propulsive force peak of different feet.

The other variables compared in this study (support impulse and push-off impulse) are not significantly different between the three prosthetic feet, which substantiates the views of Seliktar *et al.* (1986) that they represent the style of locomotion and are mainly influenced by the walking pattern rather than the actual prosthesis.

One subject was unhappy taking part in the jogging exercise. This in itself is an indication of the dissatisfaction and insecurity produced by the prosthesis. The data collected from the other two subjects confirmed previous findings. Firstly, there was a large difference between the normal foot and all prosthetic feet for all variables except the impact load rate. This confirmed the asymmetry noted for walking, and also suggested that the subjects were controlling the use of their prosthesis. It is noted for example, that the load rate is similar to that produced during walking and it is expected that this would increase with speed of locomotion. But this did not clearly happen, suggesting that subjects carefully controlled their foot placement during jogging. Secondly, there were few differences between the prostheses, and this again may be due to the conscious control of the foot as noted above. The only significant difference found was in the propulsive impulse, which was much lower in the Jaipur foot. The trend previously observed in walking, i.e. the SACH foot producing the lowest and the Jaipur foot the highest forces, was seen here also.

The small number of subjects used in this study has not limited the interpretation of the data or its generalization.

The differences between the normal and prosthetic feet are large and highly significant even with a group of subjects of this size. The differences amongst the prosthetic feet where it is substantial such as in shock absorption characteristics, is also highly significant. Where there are no significant differences, the differences are small, and it is unlikely that a larger number of subjects would lead to substantially different conclusions. Further, there is a consistency between those parameters where significant differences exist (i.e. shock absorption capacity) and those where it does not (i.e. locomotor style).

Conclusions

In conclusion it can be stated that:

1. The ground reaction force data has been successfully used to quantify shock absorption characteristics of prostheses and their effect on locomotor style.
2. The SACH foot has a better shock absorption capacity than the Seattle and Jaipur feet.
3. The performance of the Jaipur foot is more natural and nearer to the normal foot as compared to the SACH and Seattle feet.
4. There are no other significant differences in gait style produced by the SACH, Seattle or Jaipur feet.

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