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Gait Comparisons of Trans Tibial Amputees with Six Different Prosthetic Feet in Developing Countries

P Lenka, R Kumar

Department of R&D, NIOH, Kolkata, India

Abstract

Gait study in amputees using prosthetic foot ankle mechanisms used in developed countries have been addressed by many authors however very few have been done in the developing countries. The objective of this study was to compare gait parameter in six different prosthetic feet in trans tibial amputees, commonly used in developing countries. The stride parameter, vertical ground reaction force, gait efficiency and quadriceps muscle activities were studied in different feet using Computer Dynography (CDG) gait analyzer. The raw data of force and electromyogrpahy (EMG) sensors of gait analyzer were filtered, processed and analyzed with help of MATLAB 7.0. A blue tooth enabled heart rate telemetry system was used for calculating gait efficiency in terms of physiological cost index (PCI). Seven young and active male trans tibial amputees were recruited in this study and each of them were tested with each of the following prosthetic feet: Solid Ankle Cushioned Heel (SACH), Dynamic (Ottobock), Ranger, Jaipur, Greissinger and Regal. Results indicated that sound limb was exposed to more ground reaction force than the prosthetic foot irrespective of the foot type. However, velocity, cadence and gait efficiency was higher in Dynamic foot. The results of EMG analysis in quadriceps showed that the subjects using Greissinger foot mimic the muscle action of normal human locomotion.

Key Words: Gait Analysis, Ground Reaction Force, EMG, Prosthetic Foot, Trans Tibial Amputee.

Authors and their affiliations
Dr Prasanna Lenka, BPO, M Tech, PhD, Lecturer in Prosthetics and Orthotics, National Institute for the Orthopaedically Handicapped (NIOH), BT Road, Bonhooghly, Kolkata
Dr Ratnesh Kumar, MS (Ortho), DNB (Rehab), Director, NIOH, BT Road, Bonhooghly, Kolkata

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Correspondence
Dr Prasanna Lenka
NIOH
BT Road
Bonhooghly
Kolkata 700090

Tel : 91-33-25313232/1248
Fax: 91-33-25318379

E-mail: lenka_pk@yahoo.co.uk
Web: www.nioh.in

Introduction

Basic requirement of lower limb prosthesis is to restore appearance and lost functions in individuals with amputation. Prosthetic foot is an important component of trans tibial prosthesis. Load bearing, leverage, shock absorption, stability and protection are the functions of feet in lower limb prosthetic management[1,2]. New prosthetic materials and designs have broadened the range of prosthetic feet available in the market, thus it is becoming more difficult for prosthetist and prescribing physicians to select appropriate foot to suit an individual amputee. Prescription of prosthesis for lower limb amputees is primarily based on empirical knowledge and subjective experience of physicians, therapists and prosthetists[3, 4], however ideally the prescription should based on functional requirements of amputees[5]. Linde et al discussed the complexity on the precise prescription criteria in different feet in a review of literatures[6].

In developing countries selection of a prosthetic foot depends on many factors: amputees' physical and psychological attributes, financial resources, availability and maintenance of feet. John Craig reported in his study that in low-income countries financial resources are quite limited and the functional demands on prosthetic feet are extreme[7]. In the consensus of International Society for Prosthetic and Orthotic (ISPO) conference regarding appropriate orthopaedic technology for low-income countries, Poetsma summarized that foot is still the weakest part of the prosthesis and improvement required in terms of durability without losing properties is needed for good gait[8]. Gait analysis has been considered as a useful tool for evaluating an amputee's prosthesis by providing objective measurements that characterize the walking pattern[9]. Many experiments on quantification of gait parameter and energy cost have been extensively studied on dynamic and energy storing foot in amputees from developed countries[18-20,23]. Pamela et al suggested Flex foot increases biomechanical efficiency in comparison to conventional foot piece and demonstrated minimal difference in energy cost when walking at slow speed[10]. In a pilot study comparing mechanical efficiency of SACH, Seattle and Golden Ankle Prosthetic feet, it was reported that Golden Ankle feet store and retrieve more energy than SACH and Seattle foot and the time to reach foot flat was less in Golden ankle than SACH and Seattle[11, 17]. Powers et al explained the role of prosthetic foot design on sound limb loading and also found relation to gait velocity[13]. Most of the studies on prosthetic feet were carried out on costly dynamic and energy storing foot. Due to economic constraints, manufacturers and voluntary organizations attempt to copy the models of feet like SACH foot. Unfortunately some of these feet develop problem due to the use of inferior material or poor manufacturing techniques. Few investigators have reported gait studies on prosthetic feet used in developing countries. The clinical field trial of Jaipur prosthetic technology for trans tibial amputees has been extensively studied by Jensen[14] but gait studies done to compare Jaipur foot need to be reviewed. The purpose of this study was to compare the gait parameter and PCI[16] in low cost prosthetic feet (SACH, Jaipur) and relatively costlier dynamic feet (Dynamic (Ottobock), Ranger, Jaipur, Greissinger and Regal) available in the developing countries in randomly selected rural and urban young active male persons with trans-tibial amputation.

Material and Methods

Seven active male unilateral traumatic trans-tibial amputees (31±3.3 years of age) were randomly selected for this study. A case history format, questionnaires as per published PEQ[15] (Prosthesis evaluation questionnaires) were filled up for each and the consent form was duly signed. All the subjects were give a general health check up and counseling in addition to the proposed gait study. The details of subjects are given in Table 1. The inclusion criteria were:

1. Age between 25 to 35 years.
2. No residual limb pain, swelling or pressure sores.
3. No major gait deviations
4. Stump length of 40% to 60% of normal segment length
5. No musculoskeletal abnormality
6. Not using assistive device

[Please insert Table-1 here]

The above criteria were to minimize gait variability due to amputees' condition. A height adjustable endoskeletal stain less steel pylon with both socket and foot adapter was fabricated for each subject. Similarly a polystyrene resin with cotton and fiberglass laminated patellar tendon bearig (PTB) socket and a liner were made using low cost polyethylene foam for each subject by an experienced certified prosthetist. The details of the subjects' prosthetic history and cause of amputation is given in Table 1. During the prosthesis fitment process socket, suspension and adjustable pylon were kept the same in each subject, only the feet were changed and tested in a random order. The study compared 6 prosthetic feet belonging to different classes of foot-ankle assemblies as follows:

Amputees	*Age/Sex*	*BMI*	*Cause of Amputation*	*Prosthesis History and total number since amputation*
S1	25/m	17.29	Traumatic	2 yrs using PTB with SACH foot, 1st
S2	35/m	17.36	Traumatic	18 yrs using Jaipur Prosthesis, 8th
S3	30/m	23.67	Traumatic	4 yrs using PTB with SACH foot, 2nd
S4	34/m	26.50	Traumatic	13 yrs using PTB with SACH foot, 3rd
S5	32/m	21.45	Traumatic	14 yrs using PTB with SACH foot, 4th
S6	32/m	24.42	Traumatic	11 yrs using PTB with SACH foot, 3rd
S7	30/m	23.16	Traumatic	2 yrs using PTB with SACH foot, 1st

Table1. Characteristics of the subjects, prosthesis history and foot type.

1. SACH – non articulated
2. Dynamic – non articulated
3. Ranger – non articulated
4. Jaipur foot – non articulated
5. Regal – single axis
6. Greissinger – multi axis

The first three of the above are based on the SACH design with different foam combinations and marketed by different companies mentioned in end notes[1-4]. After each foot fitting, subjects were given four weeks time to get accommodated to the individual socket alignment and feet. The prosthesis alignment was rechecked before testing with the gait analyzer. The same protocol was maintained for all subjects and each subject was evaluated for gait once a month for a total period of six months.

The gait analysis system used for data collection was Computer Dynography (CDG), which was supplied by Infrotronics Medical Industrial Engineering[24-28.] Each subject was made to wrap the micro-controller called ultraflex unit around the waist and a pair of foot sensors or CDG shoes of approximate size, that were put inside the shoes below the normal and the prosthetic feet to collect normalized force distribution. The skin of areas to which electrodes were attached was cleansed thoroughly with cotton soaked in isopropyl alcohol. Disposable surface EMG electrodes were placed on both the thighs corresponding to quadriceps muscles (Vastus Lateralis, Medialis and Recctus Femoris) to record the EMG Signals. Seven electrodes on each quadriceps including ground reference electrodes were placed. Preamplifier cable of EMG electrodes and cable of CDG shoes were connected to the ultraflex unit. The foot sensors data and EMG data were digitally acquired at a sampling frequency of 100 Hz and 1000 Hz respectively and stored in Memory stick of Ultraflex unit. The Ultraflex unit is a protable battery operated microcontroller unit storage facility for off-line analysis. A portable lightweight blue tooth enabled CHR- 100, 200 LAPS heart rate transmitter was secured with elastic adjustable belt at chest level and the receiver was secured at the wrist. The electrocardiography (ECG) system was used to record heart rate at rest and at load. The gait data of all the subjects was evaluated in gait and biomechanics lab of National Institute for the Orthopeadically Handicapped, Kolkata, India.

The basis for the use of this technique is explained as follows. Gait efficiency is conventionally measured by oxygen uptake. Physiological Cost Index (PCI) is the most simple and suitable method to calculate index of gait efficiency in indirect calorimetric method as reported by Butler[34] et al and the same were also used by Nelson[21] et al to compare conventional and flex foot. PCI was calculated by dividing the velocity in Km/hr to the difference of heart rate (heart rate was measured after a fixed time of 20 sec walking on plane surface and at rest) using heart rate transmitter.

All the data was analyzed in CDG software and MATLAB 7.0. The digitally collected EMG raw data was rectified, integrated and stored as percentage of maximum peak amplitude of individual gait in each sub phase of the gait cycle. The same data was also compared to visual interface of CDG software. Differences between six feet were determined by univariate repeated measures analysis of variance (ANOVA) with a single group factor for normally distributed data and two ways ANOVA for data not normally distributed. An alpha level of 0.05 was adopted for determining statistical significance. The Pearson's correlation coefficients were also determined for calculating correlation between stride parameter. The significance level was set at $p<0.05$.

Results

Stride Characteristics: A total of 15 stride parameters were calculated (velocity, cadence, stride length, gait cycle duration, double support, single support, stance duration, step duration prosthesis, step duration normal, swing duration prosthesis, swing duration normal, symmetry stance, symmetry step duration, symmetry double support, symmetry swing), out of which significant differences were found in velocity ($p=0.016 < 0.05$) and cadence ($p=0.018 <0.05$) as shown in Table 2. The velocity and cadence with Greissinger foot was found to be the highest among all the feet and significantly greater than the SACH foot and the Jaipur foot. There was no statistical difference between stride lengths using any of six foot. The symmetry of step length (Step length prosthetic side/ step length sound limb) was high in Greissinger foot (94.982 %) and less in jaipur foot (87.93%) followed by SACH foot (88.47 %).

Foot Type	*Velocity (m/min)*	*Stride Length (m)*	*Cadence (steps/m)*
SACH	52.68 ± 13.48	1.14 ± 0.199	90.5 ± 11.95
Jaipur	54.83 ± 14.10	1.13 ± 0.24	91.87 ± 10.07
Ranger	54.63 ± 16.43	1.12 ± 0.26	96.53 ± 11.47
Regel	60.15 ± 11.23	1.18 ± 0.17	101.04 ± 7.96
Ottobock D	56.91 ± 13.13	1.11 ± 0.15	91 ± 11.40
Grissinger	64.27 ± 11.34	1.23 ± 0.18	103.72 ± 11.50
Normal	66.7 ± 9.46	1.30 ± 0.149	102.8 ± 7.155

Table2. Gait Parameters during plain surface walking at self selected velocity.

Force Sensor data: The force at loading response and toe off were calculated in each subject with different feet at the self selected velocity. The mean and standard deviation of velocities of different feet is given in table 1. Peak vertical force was arithmetically averaged for each subject for total loading response with each foot at initial stance, mid stance and push off. No statistical significant difference was found with loading response of different feet in prosthetic limb ($p= 0.07$) and normal limb (0.4875). However a significant difference was found with the Jaipur foot when compare to Greissinger foot ($p= 0.047$). The load in sound limb during initial stance was made as reference axis. Figure 1 shows the loading response results in different prosthetic limbs by comparing to the sound limbs. The loading response of Jaipur found was found better compared to all other feet. Similarly the push off action of different feet compared to the sound limb is shown in figure 2. A significant difference was found in the push off action of the prosthetic limb with different feet, $p<0.05$ ($p= 0.013$) however no statistical difference was found in the normal limb of the subjects using different prosthetic feet. ($p=0.591$). A significant difference was found in the mid stance (30% of gait cycle) in the prosthetic limb ($p= 0.0018$) but there was no difference in the sound limb ($p= 0.451$).

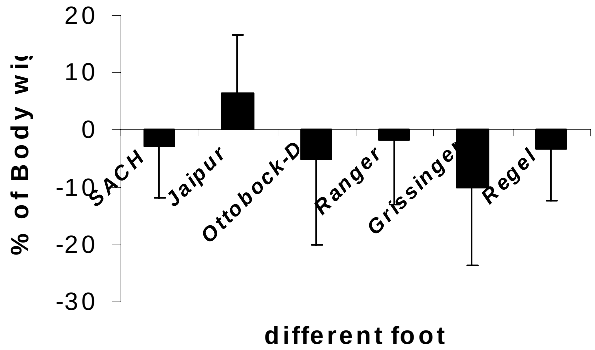

Fig 1.Loading in prosthetic limb compared to the sound limb.

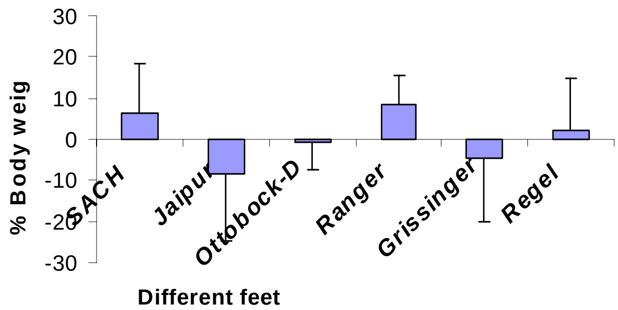

Fig 2. Push off action in prosthetic limb compared to the sound limb.

Electromyography Data: The largest and strongest component of quadriceps is the Vastus Lateralis[31]. In this study the EMG data of Vastus Lateralis (VL) were taken to verify the impact of different feet in quadriceps muscle activity. The data normalization was carried out by adopting the mean maximum value of each subject's EMG over the stride period as the reference value[29] (100%). Each stride was divided into 10% intervals and the average peak amplitude of ten strides for each subject was given a value of 100%. Similar normalization was adopted by Knutsson and Richards[30]. Each sub phase (10% of gait cycle) was expressed as a percentage of mean peak amplitude. The average value of amplitude expressed in percentage of maximum gait contraction (MGC) for seven subjects was calculated for each 10% of gait cycle. The EMG pattern of Vastus lateralis of both normal and prosthetic side with six different feet is shown in figure 3 and 4. There was statistically no difference between normalized amplitudes of EMG in the sound limbs (p= 0.656) but significant difference was found in the prosthetic limbs (p=0.011) in all the six feet. The comparison between the sound limb and the amputated limb did not show any statistical significance at any sub phase of gait cycle in an individual prosthetic foot. During the loading response of sound limb at 10% of gait cycle, maximum peak (70 to 100%) occurred with Greissinger and Ranger feet, low peak (20 to 50%) in Ottobock Dynamic and Jaipur Feet. The results showed

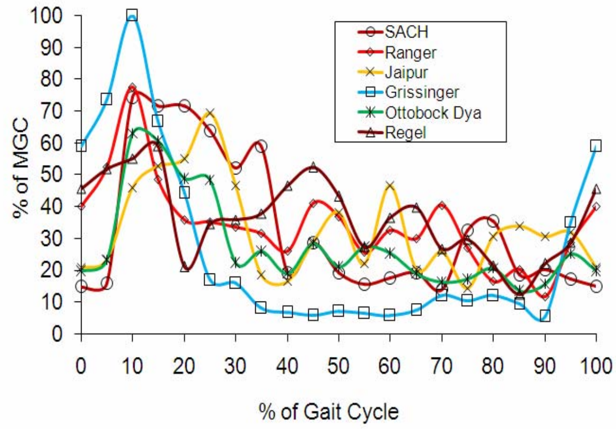

Fig 3. EMG pattern of Vastus Lateralis in sound limbs.

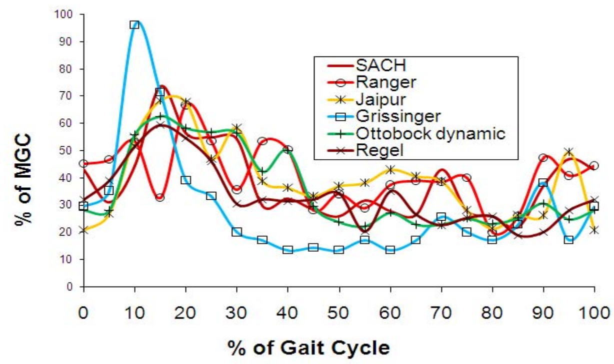

Fig 4: EMG pattern of Vastus Lateralis in prosthetic leg.

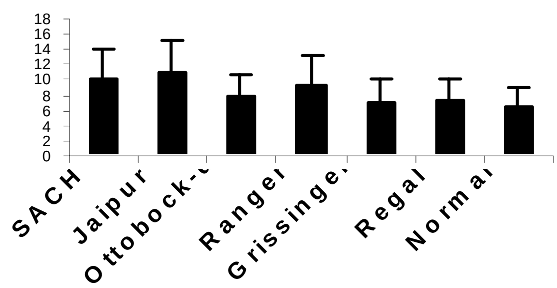

Fig 5. Physiological Cost Index of different feet in self selected velocity.

EMG activity of VL of both sound and amputated limb in Greissinger foot are similar to muscle action of normal human locomotion as reported by Winter[32,33].

PCI data: Energy efficiency was the least with the Jaipur foot when compared to all the other feet. The PCI in patients wearing all the six feet are given in figure 5. SACH foot was found better in terms of energy consumption compared to the Jaipur foot.

Discussion

Temporal-spatial parameters are useful measurements for prosthetic evaluation as they provide fundamental information about gait. The results of the study indicated that self selected walking velocity of normal subjects was in the range of 66.7±9.46 m/min but it has been reported to be approximately 70 to 90 m/min in subjects from other studies[12] and similarly a higher cadence was also reported. This difference in normal subject is due to anthropometric variations. Velocity provides a better indication of person's walking ability than any other gait parameter and should be considered in selecting a prosthetic foot[36]. Wagner indicated that self-selected walking velocity of both dynamic and SACH foot ambulation was below the normal values, which were in agreement with our findings[22]. The mean velocity of SACH foot and other dynamic feet were reported 80% and 90% of normal respectively[37], the similar results were found in our study. The other stride characteristics did not show any statistical difference in the two way ANOVA study by taking both subjects and feet in groups, similar finding were reported in the other gait studies[37,38]. It has been suggested that symmetry between the sound and prosthetic limb is the best method to evaluate different prosthetic feet[12], however our study did not show any statistical difference on the symmetry parameters but performance of different foot in terms of symmetry was differentiated.

The results of forces data indicated that sound limb faced more load than amputated limb irrespective of the feet type, same results was also reported by Powers[13] et al and Snyder[38]. As reported by Chao[39] et al the initial peak of vertical force in normal subject is 11% more than the body weight. The results showed that the Jaipur foot loading response (7% of the body weight) was more close to normal and similar findings were made in a biomechanical comparison between SACH, Jaipur and Seattle foot Arya[40]et al. Powers[13] and colleagues discussed that the prosthetic foot design played a significant role in contributing to the sound limb loading due to dorsiflexion range of motion of dynamic foot. Jaipur foot was found to transmit 9% less body weight in the push off phase due to it high flexibility and mobility. As reported by subjects during training session in our laboratory that they prefered to walk on the heel in Jaipur foot and they put more weight on heel than at toe at toe off. It was theorized that increas in the terminal stance dorsiflexion reduced the need to heel raise for tibial progression, thus minimizing the elevation of body centre of gravity and thus consuming less energy in comparison to the other feet, however as per PCI results Jaipur foot had higher energy index in comparison to all other feet expect SACH foot. The weight factor of Jaipur foot in comparison to all other feet may be responsible for high energy consumption.

The results of EMG analysis of sound limb in two ways ANOVA with a group factor of foot showed no significant difference p= 0.656 but with a group factor of phase 0 of the gait cycle showed a significant difference p= 0.0041. The EMG analysis is important in the analysis of the role of the prosthetic foot in different phases of the gait cycle by putting the duration (Gait Cyle) and amplitude of muscle activity. The EMG patterns of quadriceps muscle in contra lateral limb of the amputee subjects were not affected by changing different feet and similar results were found in the EMG analysis by Cuham[41] et al. The EMG pattern of Greissinger foot showed consistence in both the sound and the amputated limb EMG activity. Perry[24] also supported the results of peak amplitude of quadriceps in the sound limb at the initial phase of gait cycle that the primary shock absorption mechanism during the loading response was maintained by knee flexion and quadriceps function eccentrically to restrain the knee flexion.

Conclusion

The results of this study indicate that sound limb takes more load than the prosthetic limb during loading response irrespective of the type of terminal device which has already been established by many literatures as discussed, however, the results of the second peak of ground reaction force or push off concluded that push off action is poor in Jaipur foot. The symmetry of SACH foot was found better than the Jaipur foot but was less than the other dynamic feet. Greissinger foot mimics more natural gait with respect to symmetry, velocity, energy consumption and muscle activity. The amplitude EMG of quadriceps in different phases of gait cycle is found to be a better method to differentiate dynamic function of the prosthetic foot. Two way analysis of ANOVA in group factor foot and subjects showed variation of gait parameters in the individual subjects, which shows that the biomechanical character of prosthetic feet is not the only criteria for selection of the foot type but the subjects acceptability, habitat, activity and psychosocial condition may also be a factor in selecting the foot type.

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Suppliers

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2. **Jaipur Foot**: Bhagwan Mahaveer Viklang Sahyata Samiti, Swai Man Singh Hospital, Jaipur- 302004, India. www.sms.com
3. **Greissinger Foot** (1A30), **Dynamic-Ottobock** (1D10): Ottobock Health Care India Pvt. Ltd., Behind Fairlawn Housing Society, Sion-Trombay Road, Chembur, Mumbai-400071. www.ottobockindia.com
4. **Ranger Foot**, Regal Single Axis Foot: Endolite India Limited, A-4, Naraina Indl Area Phase-1, New Delhi 110028. www.endiliteindia.com