Comparison on Jaipur, SACH and Madras Foot

A Psychophysiological Study

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Abstract— **Owing to the large number of persons with disability in India and around the world, there is a growing demand for investigation and progress in prostheses or artificial limbs. This study encompassed several parameters for selection of prosthesis such as condition of patient, availability, cost, material properties, compatibility and comfort. Comparison and analysis of different low-cost non-articulating solid ankle artificial feet was done by evaluating the values of the material property tests for the common materials used in various feet and simultaneously verifying these results through subjective feedback. By performing theoretical study as well as material analysis of the three commonly available prostheses in India, viz. Jaipur foot, SACH foot and Madras foot, material properties such as hardness, relative density, shrinkage, flex crack growth etc were quantified. These results were then compared with subjective feedback received from users to determine the most suitable configuration for various conditions.**

Keywords- amputation, prosthesis; material fatigue, MCR,

I. INTRODUCTION

Artificial legs, or prostheses, are intended to restore a degree of normal function to amputees. Mechanical devices that allow amputees to walk again have probably been in use since ancient times, the most notable one being the simple peg leg [7]. Surgical procedure for amputation, however, was not largely successful until around 600 B.C. Armorers of the Middle Ages created the first sophisticated prostheses, using strong, heavy, inflexible iron to make limbs that the amputee could scarcely control. Even with the articulated joints invented by Ambroise Paré in the 1500s, the amputee could not flex at will [6].

In the 19th century, the American Civil War raised interest and led to advanced technology because of the high amount of amputations. The twentieth century has seen the greatest advances in prosthetic limbs. The first major improvement of the 20th century came in 1912, when an aluminum prosthetic leg was created by Marcel and Charles Desoutter after Marcel lost a leg in an aviation accident. Materials such as modern plastics have yielded prosthetic devices that are strong and more lightweight than earlier limbs made of iron and wood. New plastics, better pigments, and more sophisticated procedures are responsible for creating fairly realistic-looking skin.

In India, by the end of the twentieth century the most commonly used non-articulated artificial feet were SACH foot, Jaipur foot, Madras foot, and other SACH derived artificial feet. A government census carried out in 2001 showed that there were 25 million disabled people in India-2.13% of the total population. Seventy five per cent of them lived in rural areas, 49% were literate and only 34% were employed. India’s physical rehabilitation sector was coordinated by the Ministry of Social Justice and Empowerment. Since a major percentage of amputees belong to rural areas, there are three major types of low cost artificial feet which are easily available BKP in India [1, 3].

The objective of this study involves identification of factors which play role in selection of prosthesis, such as which kind of prosthesis is required, which in turn depends on the condition of the patient, length of the stump (remnants of the hand after excision of damaged part from the hand) etc. This is followed by a study of the available low cost artificial feet in India, and also investigation into material properties, which include hardness, degree of abrasion, relative volume loss, flex crack initial growth, weight bearing capacity etc. The next step is the study the comfort levels of different types of prosthesis feet through self assessment questionnaires which would include the patient’s feedback before and after prosthesis. The final step is the extensive analytical study of Jaipur foot and enumeration of the amendments that could be suggested for the Jaipur foot and the ways by which shortcomings of the Jaipur foot could be overcome.

A comparative study by Lenka and Kumar [1] deals with six different artificial feet on the basis of biomechanical analysis which included gait cycle, EMG and ground force reactions analysis. It was done using ANOVA method of variance analysis for establishing the values required as the deciding factors for an efficient foot. Arya deals with the biomechanical study of Jaipur, SACH and Seattle foot. The biomechanical analysis included kinetics and kinematics characteristics like propulsive and heel strike forces, support and braking impulses and shock absorption. Total locomotion was analyzed using these gait cycle events and parameters [2].

A paper by Cummings on prosthetics in the developing world throws light on the factors, depending on which prosthesis could be a success in India. It also gives a review of the different fabrication techniques and the alternative materials which can be used in prosthesis. The various technical aids and systems which are used for prosthesis along with the other prosthetic technologies have been described [3]. The materials used initially were replaced by time tested and more reliable materials like HDPE shafts. Cost analyses have also been given to prove its cost effectiveness. The end users benefit a lot which has been proved by the example of dancer Sudha chandran [4]. A manual by Tarun Kumar Kulshrestha was issued by the Jaipur foot organization which deals with the fabrication of the foot starting from the wrap casting, measurements to the molding, baking and fitting. It also covers alignment and the problems related to stump lengths. Jaipur BKP and knee prosthesis have been discussed in detail [5].

Eugene Wagner highlighted the composition of SACH foot and the materials which are preferred and could be used in SACH foot. It also deals with drawings which suggest the step by step processing and manufacture of the foot. The process of making SACH foot is discussed in detail, along with the procedure and materials used. A paper by Jody Van Rooyen mainly dealt with the measurement of mechanical fatigue in the prosthetic SACH foot and discusses the drop test, compliance and fatigue which are measured to analyze the efficacy of a SACH foot. The criteria have not only been set to mechanical and material tests, but also the biomechanical analysis and foot kinematics during a gait cycle have been taken into account [7].

In recent years technical innovations have combined to make artificial limbs much more comfortable, efficient, and lifelike than earlier versions. Future innovations are likely to depend on the interaction between three powerful forces—amputees' demands, advances in surgery and engineering, and healthcare funding which is sufficient to sustain development and application of technological solutions.

A. Jaipur Foot

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 structural blocks simulating the anatomy of a normal foot as shown in 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 dye to give it the shape and cosmetic appearance of a real foot (Ramchandra Sharma and Sethi, 1978 and 1988). It is probably one of the cheapest commercially available prosthetic feet. However, its production is labor intensive and standardization still remains far from satisfactory. Currently it is being used in India and six other developing countries. The main feature of the Jaipur Foot is that it does not require any shoe, i.e., amputees can walk barefoot. It is made of waterproof material enabling amputees to walk in wet and muddy fields. It permits enough dorsiflexion and other movements necessary to adapt itself while walking on uneven surfaces. It is the most cost-effective foot-pieces available in the world and it is light in weight.

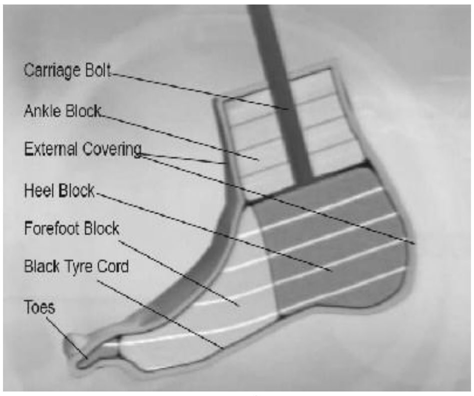

Figure 1. A sagittal section of the Jaipur foot

Manufacture of the Jaipur foot occurs in three steps, viz. (1) Rubber sheet formation, (2) Testing of the rubber/material, (3) Manufacture of Jaipur foot. For the sole, tread rubber compound is used. The rest of the foot is filled with cushion rubber compound which is lighter and has more resilience than the tread compound. The rubber is reinforced with rayon cord dipped in rubber gum. The foot is covered with skin colored rubber compound. The Metatarsal Block is made up of single piece of sponge rubber placed in the metatarsal region. This provides the stability shape of the forefoot. The length of this block corresponds to the length of the metatarsals from the base to just before the head of the metatarsals i.e. up to the balls of the toes. It is higher medially & posterior and tapers down gradually laterally & anteriorly. The anterior end of the block has a curve simulating the curvature of metatarso-phalangeal joint. Sponge rubber used in the Sponge Rubber Block process is from the sole of V strap chapels (thongs). The Sponge rubber block extends from heel to the posterior part of metatarsal block i.e. it fills the hind part of the foot. Pieces of sponge rubber sole are glued one over the other to a required height. The stump mould is placed over the top layer & the outline is carved out so that the lower portion of the stump mould snugly fits into the sponge rubber.

B. SACH foot

The Solid Ankle Cushioned Heel (SACH) prosthetic foot was designed in 1958 by Eberhart and Radcliffe (Gailey 2005) as shown in Fig. 2. It is used in various parts of India. SACH foot is an artificial foot having a wooden keel which acts as a solid ankle as well as a portion of heel. It has a flat arch portion, a rounded lower front end portion and a flat top; a curved instep portion.

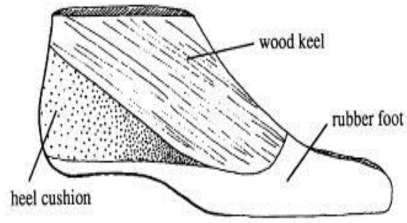

Figure 2. A sagittal section of the SACH foot

A reinforcing member comprising a highly resilient synthetic resin (nylon) strip is placed at the rear end to the above mentioned flat arch portion. Its front end extends into said toe portion to give it predetermined flexibility. SACH is also made with predetermined variable density and a toe portion of predetermined flexibility [8]. The keel is made to contribute to a portion of heel and its density and toe flexibility are controlled by composition gauge, length and number of synthetic resin (nylon) strips. The resin bonds the keel with reinforcing member used.

SACH foot is comprised of (1) an inelastic keel or core made of wood without any ankle joint (2) a molded polymer of rubber completely covering the core, except the portion where it comes in contact with the artificial limb (3) either a flexible steel spring as a band of belting material bonds with the core and extends forward to the front end and thereof into the toe section of molded portion of foot (4) cushion heel of microcellular rubber.

Adhesive bonds or mechanical fastenings are used to strengthen the core, rubber and belting. The reinforcing member used is a plurality of strips or a single strip of nylon. Strips of resin (nylon or the polyamide resin) which is equivalent to polypropylene and polyolefin could also be used. The strip thickness is 3mm to 6mm which aids the degree of resilience of the reinforcing member. Nylon gives good bonding and resilience with foams such as PU resin foam which is preferably used for molding the foot. Surface coating as can be seen in Fig. 2 comprises a mixture of rubber and plastic intimately bonded by welding to a nylon strip, or a mixture of rubber latex and carbon black or toe which is coated on and bonded to the nylon strip. If desired, coating could be done using various fabrics which may give cosmetic appearance and incorporate the nylon and PU resin around the keel and associated units.

The SACH type foot requires various degrees of flexibility in the toes and density in the heel in order to provide different height, weight and other characteristics. The present SACH foot is adapted to fitting or tailoring of a prosthetic foot to meet the varying needs of different amputees. It is able to duplicate some degree of dorsiflexion but not plantar flexion due to its static solid ankle [8].

C. Madras foot

Madras foot is mainly used in the southern part of India which mainly includes Tamil Nadu and Kerala. It is a handicraft foot made in the workshop of Government Institute of Rehabilitation Medicine (GIRM). GIRM is one of the oldest rehabilitation centers in India, being the second institute in the country. It was started in the year 1959. It is formed under ALC (artificial limb center) which is a pioneer center in Asia which was funded by World Bank in the early 80's. ALC has an identity of developing it own foot piece in the LE prosthesis named as "MADRAS FOOT". It is the first customized artificial foot made in India suiting the functional need. It was designed in GIRM Chennai and hence named as Madras foot.

It is composed of (1) wooden keel (2) canvas rubber (3) hard rubber (4) soft rubber (5) swade lather. The wooden keel extends from rear to front end up till the middle part of the foot. Anteriorly it is made up of alternate layers of soft and hard rubbers which are incorporated with keel using adhesives. The layers of soft and hard rubber are fixed with rubber adhesive. The alternate soft and hard rubber layers are given at the rear part to form the heel and diminished ankle. Anterior and posterior portion of the Madras foot has layers of soft and hard rubber which are separated by the 5mm thick canvas rubber sheet. The wood used is red sedor wood and the other types of wood could also be used, for example maple, hickory basswood, willow, poplar, and linden. The lather is used is swade lather which provides it with cosmetic appearance. It has the Advantage of bare foot walking, durability and cultural modifications like toe rings etc.

II. METHODS AND MATERIALS

The materials used in the feet were tested in the physical laboratory for properties such as hardness, resilience, elasticity, toughness, abrasion, compression etc. to establish the comparison among these three artificial feet. The material property comparison will be done on the basis of the attained values and the required values by these feet and is shown in Table I. This comparison will reciprocate the efficiencies and abilities of these feet.

TABLE I. MATERIAL PROPERTIES COMPARISON OF MCR COMPOUNDS

Properties	Jaipur foot	SACH foot	Madras foot
Hardness (Shore A)	45-50	40	51
Relative density	0.4-0.5	0.5	0.4
Split tears (kg min.)	4.5	4.5	3
Shrinkage at 100ºC for 1 hr (% max.)	2	2	2
Relative volume loss in abrasion test (cc max.)	360	300	720
Change in hardness at 100ºC for 24 hrs. (Shore A)	+5	+2	+2
Flex-crack initial cut growth (cycle)	5000	5000	4000

A. Psychophysical test

Secondly, amputees using SACH foot, Jaipur foot and Madras foot were asked (Fig. 3) a set of questions to analyze efficiency and comfort of these three artificial feet. The details of the participants are shown in Table II. The different subjects reciprocated the comfort, pain or any discomfort etc on the scale of 10. This scale is taken according to six sigma scaling standards which will help in the direct numerical value based analysis and comparisons of these artificial feet on the basis of direct feedback.

Out of these feedback questions, the most important 10 were given top priorities and weightage in descending order. The feedback of a particular question from the end users was averaged to get a particular value. This value is multiplied by the weightage of the particular question to attain the correlation factor. This correlation factor for each of the questions is established for each type of artificial foot.

TABLE II. DETAILS OF THE PARTICIPANTS INVOLVED IN THE STUDY

	Jaipur foot	**SACH foot**	**Madras foot**
Numbers	24	16	14
Mean age (±SD)	44.8(±16.2)	43.6(±17.1)	46.3(±12.4)
Experience (±SD)	10.7(±6.3)	7.6(±6.3)	5.3(±3.2)

We have formed a set of 25 questions to analyze the efficiency of the foot and the training been provided to various stump length amputees. Each of the questions is rated on a scale of 10 according to six-sigma scaling standards as shown in Table III. Six-sigma standard takes values up to 6^{th} decimal units to get highly accurate results.

TABLE III. PERCEPTION SCALE OF PARTICIPANTS

Perception	**Scale**
Poor	1 – 4
Satisfactory	5 – 6
Good	7 – 9
Excellent	10

According to the six sigma scale, the gaps in the scale of 10 have been adopted so that the person is compelled to think accurately. The questions with top priorities or weightage have been taken to compare these three artificial feet using 6 sigma scaling method. The weightage values of the questions have been assigned according to their priorities for the amputees as shown in Table IV.

Figure 3. Questionnaire study conducted on a typical participant

Here W stands for priority or the weightage of the question. A stands for average value of a particular question and C stands for the final multiplied numerical values to be compared and according to the six sigma scaling method, C can be called as the correlation factor (1).

$$\mathbf{C} = \mathbf{W} \times \mathbf{A} \qquad (1)$$

B. Comparative Failure Study

1) Jaipur foot failure study

The failure of Jaipur foot is due to the four major locations at which the fatigue/cracks most probably develop or starts to develop (Fig. 4). As been stated earlier, the four major locations are at finger (mainly thumb) joint, middle part of foot, heel part of foot, socket joint of foot. It develops due to different stump lengths, difference in weights, time of usage, bare foot usage; degree of COG dislocation and hence total life span is around 3 years only.

Figure 4. Failure at the middle of the foot

2) SACH foot failure study

It is a flexible foot but with limited elasticity. The elasticity and flexibility depends on material used for flexible string, synthetic resin, rubber and the wood or core. The rubber material develops fatigue after it has been walked on for months, which consequently results in loss of balance and alignment which was acquired when foot was first fitted.

The amputation of the user ends up with a toe section that tends to curl up to become more and more flexible with use as thereby in some cases feet break as shown in Fig. 5. Hence, flexibility and strength are not only the two contradictions but also the limiting factors for the quality of SACH foot. The cracks develop mainly at heel part of the foot and middle part of the foot.

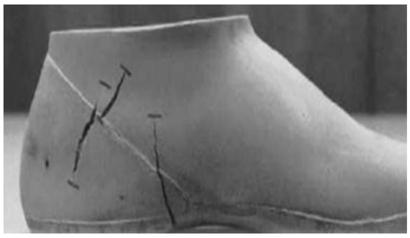

Figure 5. Shows the development of cracks at ankle region

3) Madras foot failure study

Madras foot is also prone to fatigue development. This fact is due to the friction offered to the Madras foot, since Madras foot is composed of lather and alternate soft and hard rubber sheets; they get rubbed against their surfaces in each gait cycle with time; leading to material fatigue. The adhesive used is not capable enough to withstand the weight, pressure and friction more than 2 years. The cracks develop mainly at heel part of the foot and middle part of the foot as shown in Fig. 6.

TABLE IV. SELECTIVE QUESTIONS THAT HAS BEEN RATED BY THE PARTICIPANTS USING SIX-SIGMA SCALING METHODS

W	Questionnaire	Jaipur foot		SACH foot		Madras foot	
		A1	C1	A2	C2	A3	C3
10	Rate the comfort about prosthesis weight	8.9	88.7	8.5	85	8.3	83
9	Rate the comfort while walking with prosthesis	8.5	76.5	8.5	76.5	8.1	72.9
8	Rate how often have you felt off balance	2.1	16. 8	2.1	16. 8	2.6	20. 8
7	Rate how exhausted you felt after usage	7.2	50.4	7.1	49.7	7.64	53.4
6	Sense of limping you feel?	2.1	12.6	2.2	13.2	3.3	19. 8
5	Rate your comfort to use the prosthesis with shoes	8	40	9.1	45.5	7.5	37.5
4	Rate your comfort to use the prosthesis barefoot	8.1	28	8.3	33.2	7.9	31.6
3	Have you been able to go back to social commodity?	7.8	23.4	7	21	6.6	19. 8
2	Rate the performance of training given	8.5	17	9.1	18.2	8.9	17. 8
1	Rate the aesthetics of prosthesis	9.1	9.1	9.1	9.1	8.2	8.2

Figure 6. Shows the development of crank at heel of the foot

III. RESULTS AND DISCUSSIONS

The comparative analysis of common type of rubber (MCR) used in these feet (Fig. 7) suggests that the permissible value of hardness in SACH foot (40 Shore A) helps in better shock absorption in comparison to other two feet (Jaipur foot with 45-50 Shore A, Madras foot with 51-57 Shore A). Secondly, the relative volume loss in abrasion test is much higher in Madras foot in comparison to other two feet while Jaipur and SACH foot have values for abrasion which are quite acceptable and thereby tends to increase the life span.

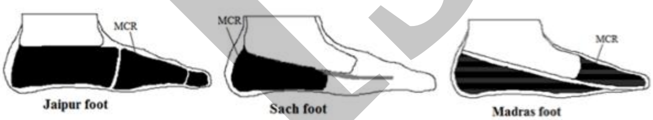

Figure 7. Placement of MCR used

The subjective feedback was utilized to prepare a data set which ranked these three types of feet. The subjective feedback results suggest that Jaipur foot excels in providing light weight comfort.

Life span of Jaipur foot (more than 3 years) is remarkable and superior to both of the SACH foot (2.5 to 3 years) and Madras foot (2 to 2.5 years). SACH foot proved equivalent to Jaipur foot in comfortable walking, while

Madras foot was ranked least in balancing with the prosthesis. Feedback also reported that exhaustion rate is maximum in Madras foot (53.4) with respect to Jaipur foot (50.4) and SACH foot (49.7). Moreover, sense of limping was graded least in Jaipur foot and SACH foot was also satisfactory, which is quite appreciable. More importantly, prosthesis which could furnish manageable speed was found to be SACH foot (76) rather than Jaipur foot and Madras foot (72, 70 respectively). Surprisingly the SACH foot (45.5) was far ahead in providing comfort with shoes as against Madras foot (37.5). SACH foot and Jaipur foot were appreciable in fetching ease in walking barefoot. Astonishing enough was the fact that many of the amputees could regain their occupation with a retrieve rate of 77.9% (23.4 as correlation factor) in case of Jaipur foot. As far as training is concern SACH foot and Madras foot gave appreciable satisfaction to end users. Last but not the least, a majority of the amputees was satisfied with the cosmetic appearance of Jaipur foot and SACH foot.

On the basis of performance Jaipur foot is a time-tested approach to aid amputees, right from the cosmetic appearance to walk, balance, comfort, and weight. However, there are some aspects like limping and exhaustion that need to be worked on. Biomechanical studies state that relocating the dislocated COG (due to limping) of the body depletes extra energy, which leads to faster exhaustion and tiredness [9]. Hence, to decrease exhaustion and improve balance and speed while walking, one has to reduce the extent of limping which applies to all three types of feet.

IV. CONCLUSION

Jaipur foot is an esteemed organization serving more than 1.2 million of people in the nation and abroad, with efficacy unmatched. It is efficient in providing light weight, comfortable, durable, artificial feet for rehabilitation of the physically challenged and the handicapped. Jaipur foot is time tested and has been proved on the grounds of material properties like hardness, abrasion, tensile strength, relative density, resilience and hence outweighs Madras foot and SACH foot in composition and performance as well, be it comfort while walking, be it lesser exhaustion rate, be it occupation retrieval rate, be it aesthetics and be it socio-cultural acceptance.

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