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Partial Foot Amputation, Finite Element Analysis of Foot and Manufacturing of Prosthtic Sockets: A Review

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Abstract: *The objective of this paper is to study partial foot amputation and its types, various loading conditions and finite element analysis of foot and prosthetic sockets used for lower limb loss persons. Partial foot amputation causes due to vascular insufficiency, trauma, frostbite, limb deficiency, diabetes and its complications. Finite element analysis becomes more feasible in biomechanical application due to its ability to give better results with complicated boundary and loading conditions. To give better gait cycle to partial foot amputation person carbon fiber foot plates or prosthetic sockets are used which are made up with traditional method or additive manufacturing method*

Keyword: *Partial foot amputation, static analysis, dynamic analysis, additive manufacturing, foot plate, prosthetic socket*

I. Introduction

Ambulation is an ability to walk from one place to another place independently with or without any assistive device which is difficult process and made easy due to architecture of foot. Human foot is most important shock absorbing as well as weight bearing structure in body. The structure of foot is complex in nature shown in Fig. 1. It contains 26 bones, 100 muscles with 33 joints, tendons, ligaments, with vessels, fatty tissue and nerves. The human foot contains three zones namely, forefoot, mid foot and hind foot [1]. Amputation is surgical removal of body part e.g. fingers, foot, hand etc. According to Vital and Health statistics[2], in 1996, it was found that, 1.27 million Americans living with lower limb loss and it is calculate that, by 2050 number of people living with lower limb loss will more than 3.6 million[3]. Partial foot amputation is the common type of amputation, due to vascular insufficiency, trauma, frostbite, limb deficiency, diabetes and its complications[4][5]. Diabetes patient may go under depression due to fear of amputation [6]. There are 1, 50,000 patients have PFA problem because of trauma and disease. It is mostly founds in older persons (above 40 year of age) with diabetes. As the number of older person increases rate of PFA will also increases [7]. There are different levels of PFA those can be described in different manner. Some amputations are longitudinal, mean they can affect foot along its length and other amputations are transverse, and mean that they transect a portion of foot. There are four types of amputation with respect to foot shown in Fig. 2.

Fig.1 A. Phalange B. Metatarsal C. Calcaneum D. Talus E. Cuboid F. Lateral cuneiform G. Middle cuneiform H. Fibula

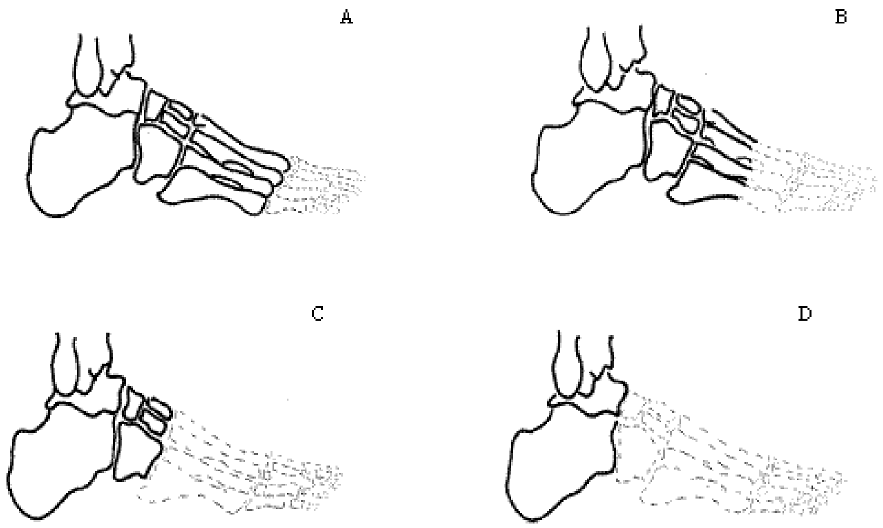

Fig.2 [5] A. Metatarsophalangeal joint B. Transmetatarsal C. Lisfranc D. Chopart amputation

Transmetatarsal amputation is a process in which removal of one or more toes of foot along with some portion of metatarsal bones. Lisfranc and chopart, these two were introduce in 19th century by French surgeons. Lisfranc is disartculation of metatarsal joint and chopart shortens the foot by removing mid and fore foot. John H. Bowker discuss about some advantages of partial foot amputation, PFA can carry body weight on residual foot and there is no more alteration of body as compare to below knee amputation. Partial foot amputation does not dependent on prosthesis. In amputation process, main objective of surgeon is to cover maximum length of foot because normal gait pattern is largely dependent on length of toe-lever remaining. Mancini L. et al. [8] conduct a survey and found that there are 15% of diabetes person cause foot ulcers. According to Dennis J. Janisse [9] there are some certified pedorthist who are specialist in shoes fitting and modification and helps to prevent amputation and ulceration by providing proper footwear. Some of the factors taken into consideration are shear force (in the presence of sensation of foot), friction and pressure inside the shoes, because it is suggested that excessive shear may cause damage to tissues. This happens because of repetitive friction between skin and layer of shoes. So there are some techniques available to reduce shear like, shear reducing socks of acrylic blend fiber and lubrication also used to reduce the shear. On the other hand only 27 mm of hg of pressure is required to block blood vessels and deprive tissue of oxygenated blood supply and constant pressure for 30 min and more is lead to loss of tissue viability and also leads to secondary amputation [9].

II. Finite Element Analysis

1.1 Loading conditions

Static condition contains standing on one foot (full weight), standing on both feet (semi weight bearing) and sitting with resting foot (Partial weight bearing). Foot pressure for static condition can be obtained with the help of pressure mat or by foot impression by ink. Fig. 3 shows outline of plantar foot pressure. In addition to that foot impression during semi and partial weight bearing condition depends on flexibility of foot. During full weight bearing condition flexible foot have impression similar to flat foot. However, for semi weight bearing condition foot represents normal foot. On the other hand dynamic condition includes walking; jumping, running etc and forces are different for different condition. The foot shape is may be different due several motions at joints. These joints allow different ranges of motion and therefore the foot shape changes. At the ankle joint, a mechanism allows dorsiflexion and plantar flexion movement as shown in Fig. 4 and 5. Generally normal foot allows 15 to 20 degree of dorsiflexion and 40 to 50 degree of plantar flexion. Inversion and eversion these are also considered as movements of foot with respect to direction as shown in Fig.6. A normal foot allows 30 to 50 degree inversion and 15 to 20 degree of eversion. Each movement has its own velocity, acceleration, and displacement requirement. It is difficult to consider all activities and forces acting on the foot base on each Activity.

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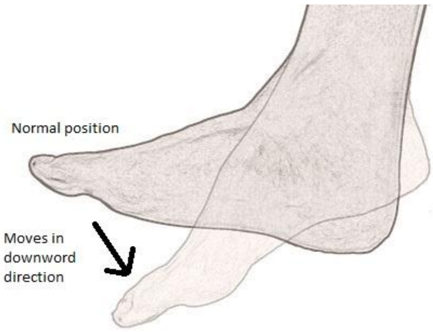
Fig. 3 Outline of foot



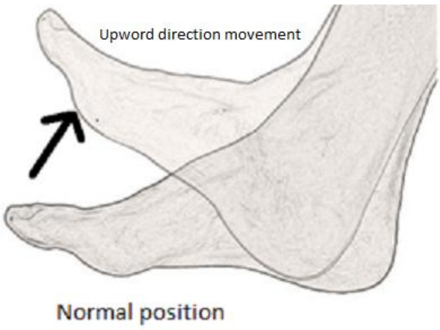


Fig.4 Plantarflexion **Fig.5** Dorsiflexion

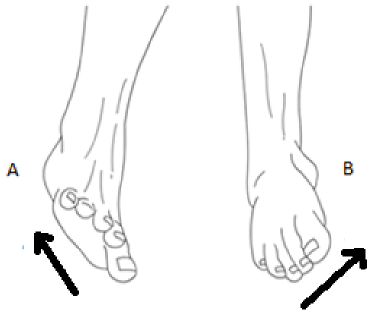


Fig.6 A. Eversion B. Inversion

2.2 FEA of foot

Finite element analysis is a software technique to find out the behavior of product, that means how it reacts to forces, vibration and other physical parameters. It will give results which shows whether a product is going to break. Finite element method become more important in biomechanical application because of its potentiality of modeling structures of different geometry and having complex material properties and easy to simulate complicated boundary and loading condition in both static and dynamic condition. In case of finite element analysis of foot, static and dynamic, stress distribution find out in foot during its three phases i.e. heel strike, mid stance and toe off. Weng pin chen et al. [10] did a 3D stress distribution analysis on barefoot during push off and mid stance application. He prepare 3D finite element model of right foot of 24 years old person

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(male). To find the geometric construction of foot CT scan images of foot were obtained. Forces and moments (loading conditions) applied on the foot find out with the help of ground reaction force and plantar pressure measurement concept. The angle variation with respect to ankle joint i.e. Dorsiflexion and plantar flexion movement with respect to velocity at 20 mm/sec was calculated. From above procedure it is found that the pressure in forefoot region gradually increases from mid stance to push off. T. M. Chu et al. [11] give static finite element stress analysis of polypropylene, for ankle foot orthosis (AFO). AFO is used for foot drop application. In this study 3D model was developed using computer aided design program PATRAN and analyzed using FEM program ADINA. PATRAN is world's most widely used pre and post processing software for FEA and ADINA is used for linear and nonlinear analysis of structures. The loading conditions were calculated by considering the concept of ground reaction force and movement of ankle. It was found that peak compressive stress occurs in heel region and maximum tensile stress occurs in neck region of AFO during toe off.Lemmon et al.[12] prepare 2D finite element model and study the impact of shoe in sole on helpful footwear biomechanics. Utilizing X ray image[13], for 2D model stress analysis were directed on both ordinary and neuropathic feet. Jacob et al.[14] make quasi static examination of various gait phases by using 3D foot finite element model to discover tarsal bone degeneration in diabetes and furthermore for Hansen's illness.. Gefen et al.[15] made 3D FE model and carried out detailed study for bone an soft tissue and perform quasi static analysis for six different instantaneous gait phases. Zhihui et al.[16] conduct a dynamic FEA of human foot. He uses explicit dynamics. In this experiment the soft tissues of foot are assumed to be isotropic, homogeneous and linearly elastic. Exact muscle moment of ankle joint for stance phase and vertical, horizontal forces were calculated using inverse dynamics method. For gait measurement a setup was generated with 12 cameras, a six force plate array(for 3d reactions 1000Hz) and 1m long pressure plate (for foot pressure at 250Hz). GMAS and matlab are used to measure the data.

III. Manufacturing Of Prosthetic Sockets

Orthoses and prostheses are guiding devices to help people with disability like foot drop and partial foot amputation. According to ziegler approximately 2 million people are living with limb loss in United state. Prostheses are assistive devices used to restore gait cycle for disable person. The prostheses devices usually consist of joints, suspension mechanism, sockets depending on type of amputation like below or above knee , below or above ankle with respect to human foot. For above ankle and below knee amputation sockets are important for comfort and proper function. There are various devices are available to manage partial foot amputation. A book on partial foot amputation written by soderberg et al. [17] gives 44 potential design options like i) carbon fiber foot plate mounted onto shoes ii) simple socket with filler prostheses iii) Ankle foot orthoses . Carbon fiber foot plates are used to give push off. Carbon fiber plates are bend wherever force applied but can't break. Main advantage of carbon fiber foot plate is, it is light in weight with better strength. During a case study performed by P. sessoms et al.[18] found that ankle foot orthosis made up of carbon fiber material gives better push off as well as walking speed as compare to barefoot while subject is partially amputed. The traditional way [19] to deal with the design and fabrication of a prosthetic socket starts with the folding the residual limb in plaster bandages keeping in mind the end goal to catch its geometry in a cast. As they laminate the residual limb, the prosthetic palpates for potential weight focuses at bony prominences and observes their areas.. The cast of residual limb is then evacuated and after that loaded with mortar slurry.. Once the slurry is set, the mortar cast is evacuated leaving a strong model of patient residual limb. An option and quicker approach to make the positive shape uses optical scanning of residual limb. . The output information is changed over into surface geometry and imported into a CNC processing machine which then made a model of the residual limb from a foam block. Whichever strategy is utilized to make the positive model adjustment are utilized to add volume to any hard prominences or delicate ranges and volume is expelled from weight tolerant zones as controlled by the prosthetic assessment and experience. The positive attachment shape is wrapped by a semi liquid PE, PP or blend of PE and PP plastic sheet, which is vacuum formed to coordinate the shape of mold. On the other hand, carbon fiber and different materials implanted with epoxy tar can be wrapped around the positive shape and cured so as to frame more grounded lighter and more costly prosthetic attachments. Yuan jin et al. [20] gives a few stages for assembling of lower leg foot orthoses 1) Measurement of the lower leg and foot, 2) making a positive model in view of negative plaster impression mold, 3) changing the positive plaster model to coordinate the life systems of the patient, and 4) vacuum thermoforming of the AFO and fitting to the patient [4]. This regular approach to create AFO is assailed by four huge difficulties: 1) work concentrated and long manufacture time, 2) restricted material choice, 3) constrained outline adaptability, and 4) Depends on the expert's skill to achieve quality consistency. In order to overcome these drawbacks, an efficient way of manufacturing method is available i.e. Additive manufacturing (AM) or 3D printing. This technique forms a object layer by layer and produce final part without any intermediate stages. The additive manufacturing of prosthetic sockets was discovered by Rovick [21] in 1990.Stereolithography (SLA), Selective laser sintering

(SLS), Fused deposition modeling (FDM), binder jetting etc are currently available 3D printing techniques. FDM process is easy to implement and commonly uses thermoplastic material. The SLA and its CAD and computer aided manufacturing software were just available for adoption in AM of custom orthoses. Roger et al. [22] provided detailed review of AM of prosthetic socket before 2007 and had integrated the compliant socket technology in a test to measure contact pressure. Faustin et al. [23] fabricated the passive dynamic AFO's using the selecting laser sintering of nylon 12, glass fiber filled nylon 12 and nylon 11 and tested in different ways. Pillari et al. [24]applied the finite element modeling and topology optimization for the design of AFO's fabricated by SLS. The socket was designer such that the end goal that its hardness had an opposite relationship to the tissue consistence at each contact point.

Fig.7 Examples of AM prosthetic sockets, made by (a) Hertbert et al.[24] (b) Roger et al.[22] (c) Hsu et al.[25] (d) Sengeh et al.[26]

IV. Conclusion

This paper summarized three topics i) Partial foot amputation ii) Finite element analysis of foot iii) Manufacturing methods of prosthetic sockets. Partial foot amputation is the common disease, mostly finds in older person due to diabetes and its complications. There are 1.27 million Americans living with lower limb loss. There is no official record of such people in India. It is critical to have such information to understand the need of this point. Finite element analysis revealed that human foot complex in nature and each movement has its own displacement, velocity, and acceleration. It is difficult to consider all these parameters. While in assembling systems 3D printing is most encouraging innovation when contrasted with conventional approach.

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