FEA simulations of Lower Limb Prosthetics

Jashan Jyot Singh¹, Jaswinder Singh Mehta¹, Rajesh Kumar¹, Gaurav Sapra¹
¹UIET, Panjab University Chandigarh

Email: jashanjsingh0001@gmail.com

Abstract. Finite element analysis (FEA) is used to study the characteristics of various objects in different working condition for imitating real life like scenarios. The present work describes an overview of FEM simulations for lower limb prosthetics. The review will give a deep insight for stress interface and load distribution on the residual limb. It enables prosthetists to design the socket for effective functional performance. The study suggests that outcomes through FEA simulations under test conditions is needed. It has been observed that predicted outcomes using FEA were in agreement with the experimental measurements. Further, the study suggests that outcomes of the FEA analysis under test conditions may be validated through GAIT cycle.

1. Introduction

Walking is the fundamental way to maneuver which reflects the locomotive characteristics of an individual[1]. Prosthesis stands for pro, meaning forward and thesis, as placement which comes from Greek language. It partially reinstate the ability of the biological lower limb[2]. There are various reasons for the prosthetics as a replacement in amputated limbs such as aesthetics and function, it helps in restoring the mobility of the amputee and increase self-esteem[3]. The different prosthetics for lower limb are transtibial and transfemoral prosthetics. The former is for amputation below the knee and the latter having amputation above the limb. Prosthetic foot, tube adaptor and transtibial socket are included in transtibial prosthetics and prosthetic foot, tube adaptor, prosthetic knee joint and transfemoral socket in the transfemoral prosthetics.

Lower limb amputations are generally much more prominent than upper limb. Amputations are generally in older adults than younger ones. Diabetic mellitus being the most common complication behind it, but vascular insufficiency, traumatic injury, cancer and congenital limb deficiency can be one of the many causes because of which the amputation can be carried out. While amputees undergo many challenges such as physical, social and emotional but it usually depends upon person to person[4]. Prosthetics can be classified into three categories with the engineering point of view i.e. passive devices which are primitive in nature having spring and damper system. Semi active system having microprocessor technology which can alter the behavior instantaneously. Power operated prosthesis works with the help of motor which help in mobility[5].
2. Finite Element Modelling of lower limb prosthetics

The part of the prosthetics which interacts with the remaining limb of the amputee is known as the prosthetic socket. The blueprint of the prosthetic transtibial socket depend on the individual requirement of the amputee as the size of the residual limb varies according to person to person. CAD FEA has been used to develop a FE model of the transtibial prosthetic socket. The results obtained through FEA were validated by experimentally measured stresses and the obtained results through FEA were found to be accurate [6].

The versatility of the CAD-FEA can be seen through the accurate results obtained through the process. While the geometry of the bones of the residual limbs are generally carried out through CT scanning and finite element analysis are used to obtain its 3D models. CT scans were used to obtain the 2D image of the limb while imaging and de-compiling helped in constructing the 3D solid model of the residual limb. The process of formation of 3D mode was found to be fairly accurate and less labor intensive without any need of formation of positive mold and manual intervention[7]. The designing process of an above knee prosthetic socket through computer aided design process has been described in the study. The fabricating through rectified cast is also seen. It was observed that the time spent over rectifying of residual limb mold could be reduced considerably with the help of computer aided designing[8]. Hence finite element analysis aid in reducing the time in the processing of design and analysis of the geometry.

As the size of prosthetic socket varies according to the need of the individual amputee so FEA analysis is a convenient process in its designing and analysis without any hassle of physical modelling reducing the time spent on physical model. FEA was used to predict the transtibial socket fit in the study. Two different pressure data were used to foresee the fitness of the transtibial socket with the help of FEM simulations. A new set of transtibial socket was then fabricated based on the computational results and fitted to the amputee. The computational analysis was found to be an efficient method in assessing socket fit which provided accurate evaluation and helped in redesigning of the prosthetic socket even before its actual fitting and fabrication.

In another study, the analysis of the prosthetic socket were carried out using FEA simulations through which the interface stresses, deformations in the socket due to applied force with the interaction of the residual limbs was analyzed. Parametric analysis was used to investigate the consequences of transtibial socket design and remaining leg geometry in the interface stresses between the remaining leg and prosthetic socket. It was found that the variation in the transtibial socket blueprint and remaining leg structure influenced the amount of interface stresses between socket and residual limb[9]. The sensitivity to variation of parameters were investigated using the CAD model in the study. It was observed that the degree of the rectification applied to the socket was directly proportional to the presumed values of the Young's modulus. The results obtained were in agreement as expected with increase in confluence pressure in the regions of higher positive rectification[10].

A nonlinear FE model was made to predict the stress w.r.t the actual geometry and the socket modification were predicted considering the slip boundary condition and large deformation[11]. The equivalent forces and moments at the knee joints at the time of movement were calculated. Three different compliant design of the prosthetic socket were observed and FEM was used to assess its structural integrity, the release of pressure during walking at fibula head was also seen. There was a reduction of interface pressure in a single leg stance at spiral slot. Largest pressure relief was found in one version of the spiral slot with reduction of 20-80% in the local interface pressure of the stance phase [12]. The non-linear FEA was used to examine the biomechanical response of stump slipping. Then a non-linear response was obtained in the biomechanical response in slump sliding. It was observed that stump sliding was one of the defining factors in socket evaluation and peak interface stress had a minor effect on the liner stiffness[13]. A FE Model was developed to study the interface pressure between the remaining leg and the transtibial socket. The friction state between the skin and socket was obtained through contact
The influence of load transfer between transfemoral residual limb and the socket was explored in the study[14]. Saunders et al. designed the solid ankle cushioned heel (SACH) model using computer modelling and finite element analysis were done based upon the loading conditions as presented upon the gait analysis of an amputee and further authenticated through mechanical testing. The system was viable in characterizing the overall performance of commercially available prosthetic feet [15]. The stress, strain and energy stored during the stance and fast walking speed were calculated with the gait data as well as the finite element modelling together in the prosthetic foot. The efficacy of the FEA simulations were validated with the gait data and then boundary conditions were tested using FEA analysis in the transtibial amputee. Therefore parameters which couldn’t be calculated with gait data alone were obtained by the FEA and gait data together [16].

A combination of series and parallel of a damping element was introduced to a prosthetic foot design which was connected to a system of springs. The damping element having high damping constant was used to change the stiffness of the system under dynamic loading. The moment, displacement and mechanical reaction were predictable with the usage of the model and it could be useful in simulations of the response if any modifications were introduced to the original prosthetic design[17].

A flex foot was studied using FEM at three different curvature i.e. 20°(small), 35°(medium) and 50°(large) degrees for a person standing or running. The result obtained were that there were higher stresses and larger displacement in big bending foot. The peak von Mises stresses were as maximum in big bending than in medium bending and least in small bending[18]. In another study, Roll over shape (ROS) with Ground Reaction Force (GRF) were clubbed together in the optimization of the prosthetic foot. It was found that desired deformation pattern in the foot could be obtained with the stiffness profile optimization while considering ROS corresponding to transient GRFs[19]. The anteroposterior was found to be having prominence in the figuring out of the peak von-mises stress, deformation values of monolims. The optimization of the structural design of prosthesis was found to be ideal with FEM and Taguchi methods[20].

Two composite materials namely polyethylene epoxy and vinyl ester were used along with carbon fiber in the prosthetic legs blade which in turn reduced the number of layers of the carbon fiber ultimately reducing its weight and thickness. The addition of the aforesaid materials helped in reducing the strain in the existing prosthetic[21]. FE Model was used for the analysis of the structural behavior of the monolims at different shank angles and the interactivity of the limb and socket were also seen. The amount of von mises stress values at different shank design at different walking phases were observed. It was observed that shank stiffness reduced with lower applied peak stress. The deformability of shank was predicted during walking without the actual pro fitting of the prosthetic and direct measurement. The effect of shank flexibility on socket-limb interaction was explored[22]. A FE model and a concurrent multibody of the femur, tibia, socket and ESAR prosthesis of a transtibial amputee was formed [23]. The effect of friction on the residual limb of the transfemoral amputee was studied through FEM model. The friction had an effect on the soft tissues of the residual lower limb. The influence of coefficient of friction on the prosthesis, liner and soft tissues on the stress distribution between the complete system was analyzed with the FEA obtained results[24]. The study of the stresses appeared on the bone adjoining to the implant was carried out using FE Model. The amount and spread of bone stresses were compared for upper leg amputee with an Osseo-integrated prosthesis for 3 different loading conditions. A clear difference in the amount and stress distribution were observed for the 3 loading conditions [25].
Table 1. Summary of review articles based on optimization of process parameters

| S.No | Author Name | Objective | Results |
|------|-------------|-----------|---------|
| 1.  | J.C.H. Goh et al. [6]. | A CAD-FEA prototype obtaining method was proposed from the geometry prevalent CAD system. | The interface pressures were predicted reasonably well with the developed system, it could be combined with prevalent system for obtaining numerical feedback in an automated process. |
| 2.  | Zhang Shuxian et al. [7] | The limitation of the plaster casting in the traditional prosthetic socket fabrication was aimed to control and a method to form 3D models for the bones and skin of the residual limb are presented. | The construction of remaining leg and the prosthetic socket through CAD-FEA were found to be much better than previously done method, the downside was found to be the slightly higher price and processing time. |
| 3.  | T.A. Krouskop et al. [8] | A Computer Aided Design process was described in the fabrication of the above knee prosthetic socket. | The results signified the use of computer aided design in the designing of the above knee sockets. |
| 4.  | Ming Zhang et al. [9] | FEA was used to foresee the prosthetic socket fit in the study. | Two pressure data were used in predicting the fitness of prosthetic socket while using FEA. |
| 5.  | D. P. Reynolds et al. [10] | The compression of tissues in the remaining leg within the prosthetic socket had been analyzed using FEA. | The results were obtained as expected with increase in interface pressure in areas of higher positive rectification. |
| 6.  | Xiaohong Jia et al. [11] | The actual geometry of residual limb was used in the formation of its 3D nonlinear finite element model, the mechanical interplay between the socket and the remaining leg during the movement was studied with the formation of internal bones and socket liner. | The moments and equivalent forces during walking were calculated in the study. |
| 7.  | Mario C. Faustini et al. [12] | The work carried about in the study was aimed at the reduction of the pressure when the remaining limb and the prosthetic socket were in contact. | It was observed from the results that when the acquiescent characteristics are merged together inside the walls of the socket then it can be helpful in reducing the pressure which arises due to the association of the remaining leg and the prosthetic socket, this would lead increased comfort for the amputees. |
| 8.  | Chih-Chieh Lin et al. [13] | The biomechanical feedback of the stump gliding with the prosthetic socket were studied with the use of FEA analysis, the effect of the stiffness of the liner on the transtibial prosthesis were given special attention. | It was seen from the solution that biomechanical feedback of the stump sliding were highly varying. |
| 9.  | Linlin Zhang et al. [14] | The study of confluence pressure among the above knee remaining leg and the leg casing was carried out using nonlinear finite element model. | The effect of loads transfemoral remaining leg and the leg casing was analyzed in the study. |
| 10 | Marie M. Saunders et al. [15] | The motion analysis, computer analysis and mechanical testing were used in developing a prosthetic foot design. | The utility of the approach to the parametric design was seen in the study, the prosthetic foot performance was analyzed numerically with inclusion of viscoelastic heel. |
| 11 | Xavier Bonnet et al. [16] | In the study the finite element analysis and gait data were clubbed together to obtain the stress, strain and the values of energy stored in the foot through the stance position at user defined walking motion. | The FEM and gait data combined assisted in obtaining the results which were not possible through kinematic analysis. |
| 12 | Heimir Tryggvason et al. [17] | The design modification of prosthetic foot was carried out with the study directed at the changeable stiffness of the object. The work is achieved by carrying out the design modification using finite element method. | The validation of the FE model was carried out using the calculated values of a prosthetic foot. It was also found to be useful in the analysis of the functional characteristics of the prosthetics. |
| 13 | Ming-Jen K et al. [18] | The interactivity among the remaining leg and socket were analyzed using FEA while using dynamic loads in the gait cycle. | It had been observed from the study that the highest results in the stresses gain in the dynamic model but the pressure areas may increase in either only size or both in size and magnitude. |
| 14 | M. Barbara Silver-Thorne et al. [19] | FEA was used to form the model of the amputed leg limb and its socket, the changes were done parametrically and the effects due to the stress dispersal were studied. | The solutions of the study concluded that variation in both the remaining leg geometry and the socket design have an effect on the interface stresses. |
| 15 | Winson C. C. Lee et al. [20] | The different design factor’s significance were identified using Statistics- based Taguchi method in controlling of the stress and deformation within the mono-limbs. | It was concluded from the study that sagittal dimension was the most significant design factor in deciding the von Mises stress, deformation and dorsiflexion angle in the mono-limbs. |
| 16 | Linlin Zhang et al. [21] | The prosthetic racing legs [blades] were studied while using FEA process. | The value of stresses were found to be equivalent while changing the material for the same geometry, there was a growth in young’s modulus with decrease in strain. |
| 17 | David A. Boone et al. [22] | The evolution of finite element model was described and the action of mono-limbs structurally with various shank blueprints were analyzed, the interplay of the residual leg and the socket was also studied during regular movement such as while walking. | A FEM was formed to anticipate the shank deformation of the mono-limbs, higher understanding of the stress distribution was observed and the effect of shank flexibility on socket limb interaction. |
| 18 | Stacey M. Rigney et al. [23] | A FE model and concurrent multibody of femur, tibia, ESAR prosthesis and socket of a transtibial amputee athlete during sprinting were presented. | Thus, the model formulated an improvement in the calculation of energy storage presently with in vitro mechanical testing only as variance was observed with the true in vivo behavior. |
| 19 | Armando Ramalho et al. [24] | The study was aimed at development of FE Model to | Friction as a factor was evaluated using Finite Element Model in the |
estimate the effect of friction on the remaining leg of a person having amputation above the knee.

remaining leg of a person with above knee amputation.

20 Winson C. C. Lee et al[25] CAD-FEA was developed to analyze the stresses in the bone adjoining the insert. A comparison in the distribution and magnitude of bone stresses were carried out in the study for transfemoral amputees having Osseo integrated prosthesis at three different loading condition.

The above reviewed articles give an insight in the capabilities of Finite Element Analysis in the analysis of the lower limb prosthetics. It has also been seen from the literature that the mechanically conducted tests based upon ISO 16955 and the FE analyzed results were comparable with accuracy of around one percent while having maximum force of 824 N at the stance phase time of 600ms [19].

3. Conclusion

The study demonstrates the importance of FEA in the analysis of the lower limb prosthetics. It can be articulated from the analysis that FEA obtained results were near to practical measurements with socket modifications done based upon the FEA results. The effect of curvature of blade and material properties are the critical parameters for consideration while designing the lower limb prosthetics. FEA Simulations empowers to simulate different conditions which are otherwise difficult in physical conductions. Further, it helps in reducing the time in the rectification of the designed components hence improving its work efficiency. The workability of different prosthetics in similar working conditions can be checked through FEA but obtained results from simulations need to be appropriately close to the results obtained from physical testing. Further, testing conditions for simulation are required to be closer to the naturally occurring environment. GAIT analysis may provide significant data to validate these simulations.

Reference

[1]. Rajt’uková V, Michaliková M, Bednaricková L, Balogová A, Živčák J 2014 Biomechanics of lower limb prostheses  Procedia Eng 96 382–91.
[2]. Dyer B T J, Sewell P, Noroozi S  2014 An investigation into the measurement and prediction of mechanical stiffness of lower limb prostheses used for running Assist Technol. 26(3) 157– 63.
[3]. Douglas T, Solomonidis S, Sandham W, Spence W 2002 Ultrasound imaging in lower limb prosthetics  IEEE Trans Neural Syst Rehabil Eng. 10(1) 11-21.
[4]. Murray C D, Fox J  2002 Body image and prosthesis satisfaction in the lower limb amputee. Disabil Rehabil 24(17) 925-31.
[5]. Windrich M, Grimmer M, Christ O, Rinderknecht S, Beckerle P. 2016 Active lower limb prosthetics : a systematic review of design issues and solutions. Biomed Eng Online. 15(3) 5– 19.
[6]. Goh J C H, Lee P V S, Toh S L, Ooi C K  2005 Development of an integrated CAD-FEA process for below-knee prosthetic sockets Clin Biomech 20(6) 623–9.
[7]. Shuxian Z, Wanhua Z, Bingheng L 2005 3D reconstruction of the structure of a residual limb for customising the design of a prosthetic socket Med Eng Phys. 27(1) 67-74.
[8]. Krouskop T A, Muilenberg A L, Doughtery D R, Winningham D J 1987 Computer-aided design of a prosthetic socket for an above-knee amputee J Rehabil Res Dev. Spring 24(2) 31-8.
[9]. Lee W C, Zhang M 2007 Using computational simulation to aid in the prediction of socket fit: a preliminary study. *Med Eng Phys.* 29(8) 923-9.

[10]. Reynolds D P and Lord M1 1992 Interface Load Analysis for Computer-Aided Design of Below-Knee Prosthetic Sockets *Med. Biol. Eng. Comput.* 30 (4), 419–426.

[11]. Jia X, Zhang M, Lee WCC 2004 Load transfer mechanics between trans-tibial prosthetic socket and residual limb Dynamic effects *J Biomech* 37(9)1371–7.

[12]. Faustini M C, Neptune R R, Crawford R H 2006 The quasi-static response of compliant prosthetic sockets for transtibial amputees using finite element methods *Med Eng Phys* 28(2) 114–21.

[13]. Lin C C, Chang C H, Wu C L, Chung K C, Liao I C 2004 Effects of liner stiffness for transtibial prostheses: A finite element contact model *Med Eng Phys.* 26 1–9.

[14]. Zhang L, Zhu M, Shen L, Zheng F 2013 Finite element analysis of the contact interface between trans-femoral stump and prosthetic socket *Annu Int Conf IEEE Eng Med Biol Soc* 1270-3.

[15]. Saunders M M, Schwentker E P, Kay D B, Bennett G, Jacobs C R, Verstraete M C et al. 2003 Finite element analysis as a tool for parametric prosthetic foot design and evaluation. Technique development in the solid ankle cushioned heel (SACH) foot *Comput Methods Biomech Biomed Engin.* 6(1) 75-87.

[16]. Bonnet X, Pillet H, Fodé P, Lavaste F, Skalli W 2012 Finite element modelling of an energy-storing prosthetic foot during the stance phase of transtibial amputee gait *Proc Inst Mech Eng H.* 226(1) 70-5.

[17]. Tryggvason H, Starker F, Lecomte C, Jonsdottir F 2020 Use of Dynamic FEA for Design Modification and Energy Analysis of a Variable Stiffness Prosthetic Foot *Appl. Sci.* 10 650.

[18]. Ke M J, Huang K C, Lee C H, Chu H Y, Wu Y T, Chang S T et al. 2017 Influence of three different curvatures flex-foot prostheses while single-leg standing or running: A finite element analysis study *J Mech Med Biol* 17(3) 1–12.

[19]. Mahmoodi P, Aristodemou S, Ransing R S 2016 Prosthetic foot design optimisation based on roll-over shape and ground reaction force characteristics *Proc IMechE Part C: J Mechanical Engineering Science* 231(17) 3093–3103

[20]. Lee W C C, Zhang M 2005 Design of monolimb using finite element modelling and statistics-based Taguchi method *Clin Biomech* 20(7) 759–66.

[21]. Rahman M, Bennett T, Glisson D, Beckley D and Khan J 2014 Finite Element Analysis of Prosthetic Running Blades Using Different Composite Materials to Optimize Performance *Int Mech Eng Congress Expo* 10 14-20

[22]. Lee W C, Zhang M, Boone D A, Contoyannis B 2004 Finite-element analysis to determine effect of monolimb flexibility on structural strength and interaction between residual limb and prosthetic socket *J Rehabil Res Dev.* 41 775–86.

[23]. Rigney S M, Simmons A, Kark L 2015 Concurrent multibody and Finite Element analysis of the lower limb during amputee running *Proc Annu Int Conf IEEE Eng Med Biol Soc* EMBS 2434–7.

[24]. Ramalho A, Ferraz M, Gaspar M, Capela C 2020 Development of a preliminary finite element model to assess the effects of friction on the residual limb of a transfemoral amputee. *Mater Today Proc* 33 1859–63.

[25]. Adam C J, Lee W C C, Doocoy J M, Bra R, Evans J H, Pearcy M J et al 2008 FE stress analysis of the interface between the bone and an osseointegrated implant for amputees – Implications to refine the rehabilitation program 23 1243–50.