Biomechanical investigation of lower limb injuries in military scenarios: using Finite element modeling approach.

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ISLAMABAD

DECEMBER, 2019

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A thesis submitted in partial fulfillment of the requirements for the degree of

MS Mechanical Engineering

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ISLAMABAD

DECEMBER, 2019

FORM TH-4

National University of Sciences & Technology

MASTER THESIS WORK

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Acknowledgements

I am grateful for having a loving and caring family who at the end of the day put a big smile on my face. I would like to thank my beloved father, Mujahid Mehmood , who gave me the wings to fly and encouraged me to do my best, and thanks to my mother, Safia , whose constant prayers keep me going. Her prayers have always followed me and have clung to me all my life.

Thanks to my siblings Adnan and Umar for their immaculate love, tremendous support and for lifting me up whenever I am down.

And above all, thank you Almighty Allah for helping me and guiding me through this wonderful journey.

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderfulaccomplishment.

Abstract

The injuries to foot-ankle complex is common due to different type of activities , such as falls from a height especially in parachute landing where frequently damage is caused to this region. Ankle injuries results into long-term impairment due to such injuries as chance of poor vascularity increases, which affects working ability. The current research requires creation of finite element model of foot, based upon computer tomography (CT) images with an objective to develop a CAD and to predict the stress distribution within foot bones due to landing. Image processing technique was used to develop model's geometry whereas anatomical images were provided by the Radiology Department, PIMS. Meshing scheme was established through mesh sensitivity test and the finite element method is then utilized to analyze response of the foot bones. FE model incorporated realistic component structures and material properties of bones, ligaments and tendon. As the first part of study required model validated, so the stress was assessed for controlled balance standing conditions. Results were validated according to mentioned readings.The validated model was then enacted to predict the localized stress distribution in foot bones during landing with different foot postures: Flat foot, plantar flexion and dorsiflexion, under velocity based impact loading. The test results showed maximum stress in ankle region bones and joints in all three mentioned postures of foot during landing while Plantar flexed foot absorbed maximum reaction forces during landing and high stress value was observed for each foot bone in this case.

Key Words: *Computer Tomography, CAD, Finite element model*

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

The mechanical behavior of biological systems is qualified through biomechanics. Recently, finite element based modeling is preferred as computational tool for biological systems analysis dueto its complex geometry.

Human foot is contemplated as an important segment of the body, which renders the direct contact with the supporting surface. Human foot is important for all load-bearing tasks. During locomotion, the foot contributes to play an important role in shock absorption, conforms to irregular surfaces (Scott et al., 2007).

The feet should be energy efficient, supportive, flexible and stable enough so as to support the body weight, defy the ground reaction forces, move the body forward, and to get by with different types of footwear (Briggs, 2005).

All these functions of the feet are substantiated by a complex anatomy of biological materials which deforms and assimilate energy. An in-depth analysis of the deformation of foot structure is essential for the manufacturing and designing of footwear so as to avoid the injuries and to enhance the performance. The internal stress and strain distribution within some key internal components is essential to study on the bio mechanical behavior of the whole foot complex. The direct measurement of these parameters is challenging, only effective way is using comprehensive computational foot model to acquire those important bio mechanical data.

Landing is an important human locomotion and many foot problems have been associated with it , such as ankle sprain, joint dislocation and bone fracture, of the foot (Busch and Chantelau, 2003; Pontaga, 2004; Ekrol and Court-Brown, 2004).

Parachute landing is one of situation of impact landing where impact between foot with certain velocity and ground happens, in result of which ground reaction forces are generated which are absorbed by foot. Due to such forces, many foot and ankle injuries occur.
Landing is recognized as the threatening part of parachuting, especially military parachuting where injuries occur when a paratrooper comes in contact with ground and upon impact with the ground high reaction forces are generated and absorbed by paratroopers.

Majority of the parachute landing injuries imply the lower limbs of the human body. The lower limb injuries includes knee and ankle sprains of different ligaments and muscles whereas ankle, foot, and knee bone fractures are also common. Foot is the first part of human body to come in contact with ground. Ankle injuries are predominant among civilian and military parachutists. The reason behind these type of injuries is excessive impact forces, generates due to poor landing, which can be avoided through proper training (Kasturi et al., 2005). For this reason, it is necessary, that safe landing techniques should be acquired by military paratroopers to efficaciously take up the high impact forces.

However, research on this challenging problem is not that common but some experimental based research presents overall body forces, this current bio mechanical testing methods are not able to provide the internal stress values within the foot bones due to the sophisticated structure and boundary conditions of the system. To investigate controlled foot posture is challenging such as experimenting plantar flexion landing solely through extensive large panel bio mechanics test of the human movement for safety repercussions.

To assess the influence of impact forces on rear foot, mid foot and forefoot bones, computational models are used when experiments are strenuous to perform. Finite element (FE) analysis provides a platform to evaluate the internal stress distribution in a confined environment and to study the sentiency of different postures that may help both in designing of shoe and clinical application.

1.1 Research Question

Mapping stress distribution in foot bones using image based Finite element method to predict the localized deformations due to low velocity impact loading.

1.2 Objectives of the study

- Development of a realistic 3D human foot model based on CT scan data
- Development of mesh from CAD model
- Development of finite element model by applying boundary conditions, loading and contact conditions
- Simulation of various landing impact scenarios and evaluation of stress field

1.3 Motivation

Human foot holds an importance for researchers due to interest in its complex anatomy and loading it experiences in day-to-day activities. Landing is commonly employed during intensive sports based activities as an essential athletic task (Dufek and Bates, 1990). High-risk military operations also includes landing like in dismounting from trucks, running obstacle courses and parachutelanding (Amoroso et al., 1997).

Military paratroopers are more vulnerable to the risk of serious injuries rather than their civil counterparts as they carry heavyequipment during military operations. The injury risk further escalates because of the number of military operations performed in the bad weather and sometimes operations executed in night affects visibility, and in uneven terrain. Ankle injuries dominate in both civilian and military parachutists. Some studies suggest that 85–90 % of all parachuting injuries occurmostly during the landing .This all supports the belief that landing is contemplated as the most vicious phase which if not performed properly can lead to lifetime impairment(Guo, W.J., et al., 2014).

Researchers have pointed out the bio mechanical factors on finding the cause; treatment and mitigation of many foot injuries. Hence, its important to locate the biomechanics cognate with the loading of normal foot andduring its landing. The internal stress and strain information of the foot and ankle is vital in enhancing the knowledge to reach the conclusion. It is difficult to directly measure the parameters, while through computational modeling; we can acquire important clinical information.

1.4 Relevance to National Needs and Areas of Application

A 3D image based computational model of foot used in this study for stress field evaluation can highlight the information that may allow paratroopers to prevent injuries by improving PLF technique. The results of this study are applicable in

• **Healthcare industry**: For the designing and the assessment of new protective systems and to develop the posturalguidelines so as to minimize injury by update the PLF techniques.

• **Research:** Enable researchers especially bio mechanists to have knowledge of bone strength and stress distribution to design insole according to stress distribution.

CHAPTER 2: LITERAURE REVIEW

This chapter covers a review of literature relevant to the study. The chapter has divided into three major sections. First ‘anatomy and physiology’ of human foot highlighting configuration of human foot bones, and role played by ligaments and tendon in foot movement. Then types of foot injuries reported in literature and then finally, the chapter closes with explicating the role of Finite Element based analysis of foot bones under different loading conditions mentioned in literature.

2.1 The Anatomy and Physiology of Human foot

Foot consists of soft tissues, skin, joints and bones .These structures plays significant role in bio mechanical functioning of the lower limb. Both intrinsic and extrinsic muscles controlthem. Foot acts on ground, which provides support and balance while standing and plays part in stabilizes the body during walking (Abboud, 2002).

Load-bearing and propulsion are two important tasks performed by foot which requires high degree stability. Foot adapts to uneven surfaces through flexibility provided by bones and joints in foot while maintaining its functional integrity. All these multiple bones embody an arch to support the weight.
The foot and ankle complex consists of following important mechanical structures:

1- There are 26 bones in the foot which includes 7 tarsals , 5 metatarsals and 14 phalanges.

2- Metatarsophalangeal (MTP), Ankle, tarsometatarsal, midtarsal, interphalangeal, and subtalar joints arelower extremity joints which provide flexibility and resiliency to the foot structures.

3- Soft tissues which are present in foot are more than 100 in number include skin, muscles (20), tendons and ligaments. They are important in controlling movement and providing stability.

4- Foot also comprise of blood vessels network and nerves.

The foot is divided into four segments structurally, the fore foot, the mid foot, the hind foot and the phalanges.

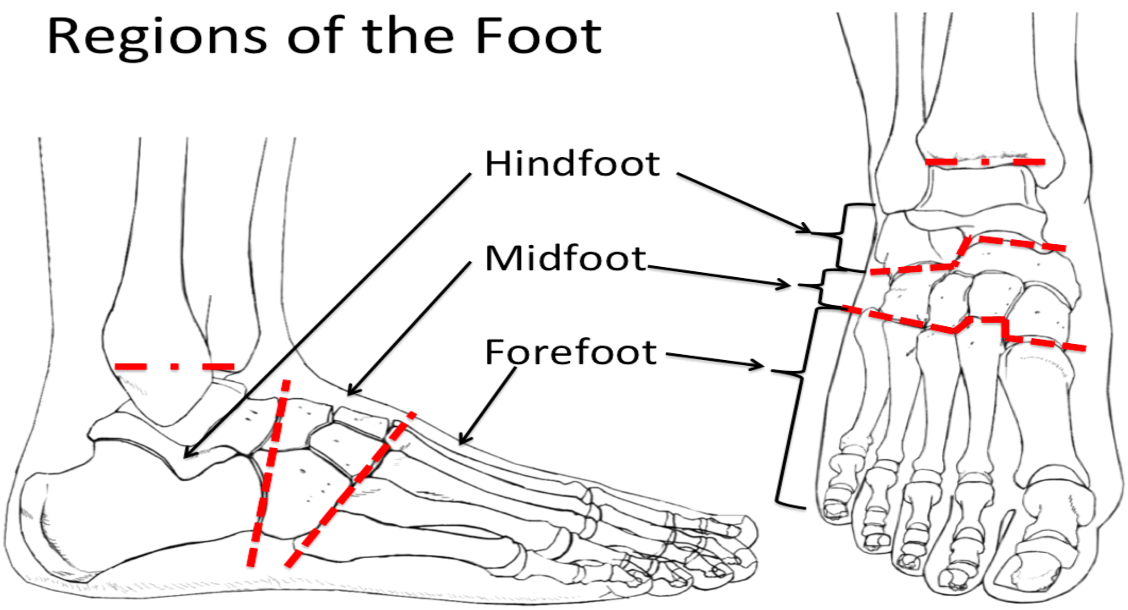


Figure 2.1: Regions of the foot

External resistance is opposed by the foot which is the last part of lower kinetic chain. The stance phase of gait requires the lower extremity to dissipate and distribute tensile ,compressive , rotatory and shearing forces , which if inadequate distributed causes abnormal movement and produces excessive stress. Due to excessive stress, breakdown of soft tissue and muscle takes place. Foot and ankle normal mechanics results into the most efficient force attenuation (Abboud, 2002).

2.1.1 Bones of the foot

Lower leg bones, tibia and fibula connected to ankle bone known as talus form the ankle joint thereby moulding a very stable structure. Calcaneus which is also called as heel bone and talus ,both together make up the subtalar joint at the back part of the foot . It permit the foot to move from side to side. Just down from the talus is a set of tarsal navicular bones that works together and forms multiple joints in order to fit together. These tarsal bones and the cuneiforms are part of the mid foot.

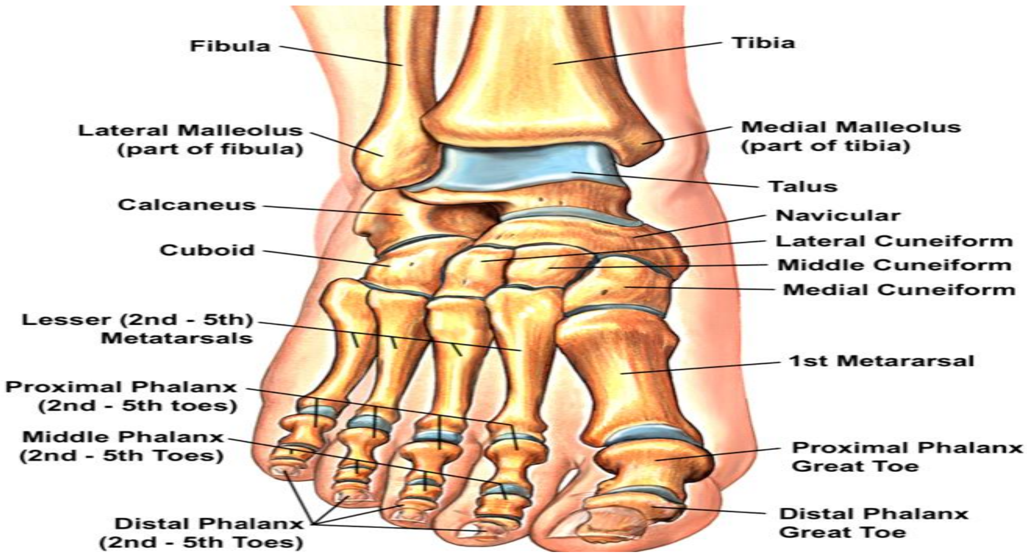


Figure 2.2: Foot Anatomy

The five long bones of the forefoot to which tarsal bones are connected, are named as the metatarsals. These groups of bones are rigidly connected, thereby restricting the movement near joints. The five metatarsal bones are however; further connected to a group of smaller bones known as phalanges, the bones of toes (Rohen and Yokochi, 1988). These bones are much thinner than the bones in the hind foot and mid foot, and are known to be vulnerable to injuries in sport or normal gait (Matheson et al., 1987).

2.1.2 Muscles, Tendons and Ligaments of the foot

The foot muscles divides into intrinsic and extrinsic muscles, which divides further into dorsal and plantar groups. These muscles provide balance during standing, stability and supports during propulsion (Abbound, 2002).

Tendons and ligaments are very important structure for the human foot. Tendon is a band of fibrous tissue , connects a muscle to a bone. Muscle contracts to pull on the tendon, which in result moves the bone. There are various tendons attaching muscles to the bones in the foot. The most essential of them is Achilles tendon, which is located at the rear of the foot just above the heel.

The Achilles tendon holds important function during walking, running, and jumping (Hof et al., 2002). The toes bend down and straighten through attached tendons located on the top and bottom of the foot phalanges.

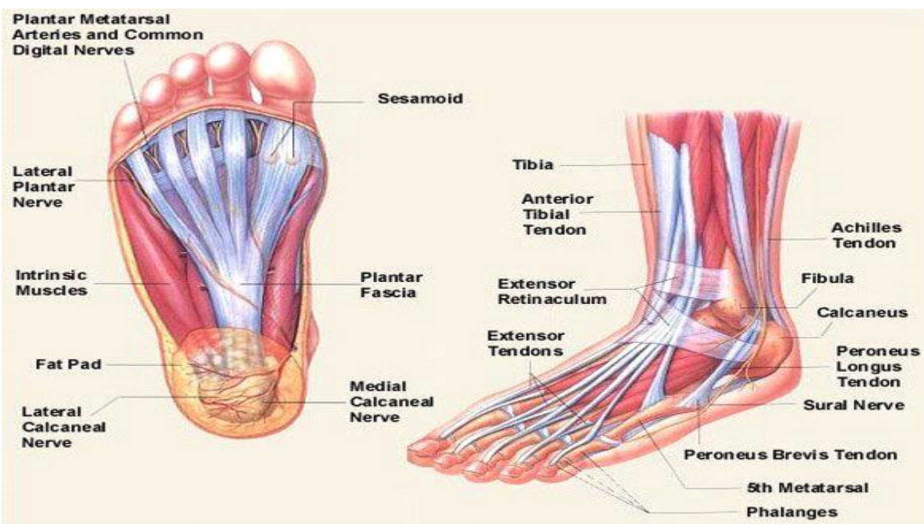


Figure 2.3: Muscles, Tendonsand ligaments in foot

Ligaments and tendons are akin to each other, ligaments annex bones to bones while tendons annex muscles to bones which make the difference. There are various ligaments in a human foot to help in holding the foot bones together. Ligaments constitute of small fibers called collagen, which are assembled together to develop a rope-like structure (Altman et al., 2002). The thickness of the collagen bundle regulates the strength of the ligament.

The major function of the ligaments is stabilizing and guiding the subtalar joint during movement. These ligaments are categorized according to their location as belonging to the subtalar joint, the metatarsal, the forefoot, or the sole of the foot. The longest ligament is plantar fascia, and it is important part of the arch extending from the toes to the heel. It connects heel bone to phalanges. Balance and strength to foot is provided by the expansion and contraction of the plantar fascia, to provide flattening and curving of the arch so as to bear the entire body's weight (Cheung et al., 2004).

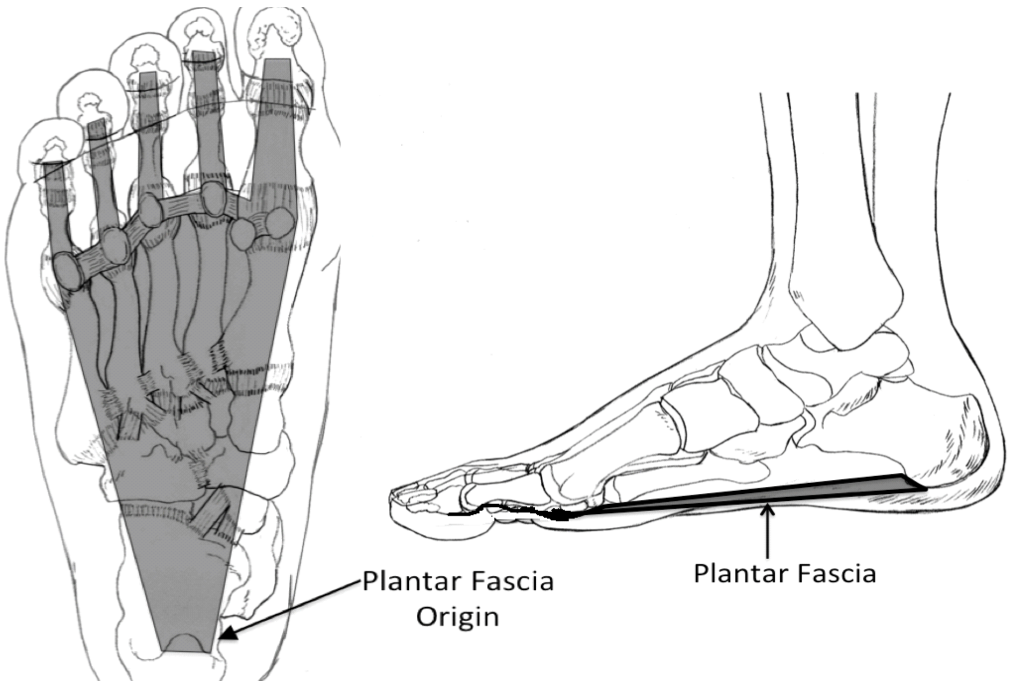


Figure 2.4: Plantar Fascia

2.2 Numerical analysis of 3D Foot model using Finite Element Method

Human foot as a mechanical structure is used for the numerical analysis following different simplified parameters regarding mechanical properties of foot bones, geometry, muscle loading and stress distribution within the soft tissues .

Simkin (1982) accomplish major discovery by developing static foot model during balance standing using matrix structural analysis , which is paradigmatic and quantitative in three dimensions. However; representing reduced result accuracy not allows a complete viability of the modelin the field of displacements.

Chu et al. (1995) worked on three-dimensional Finite Element foot model to analyze orthotic effects. This model includes the linear elastic ligaments and soft tissues, yet, foot bones were not segmented individually.

Patyl and colleagues (1996) generated two-dimensional finite element (FE) model enacting two-dimensional cross-sectional anatomization of the foot , procured from the lateral X-ray images pointing the areas of high stress for the normal and neuropathic feet during gait. Their work is a step towards the evaluation of stress distribution in both normal and disordered feet. Patyl's group (1996), in their recent studies modeled a simplified foot structure.

Next year, Genda et al. (1999) studied load transmission in the foot through constructing model of foot including 14 bones and 59 ligaments, in which ligaments were represented by spring and bones were modeled as rigid bodies. Connection between foot surfaces was designed to transfer loads.

In 2000, Gefen and colleagues worked on three-dimensional FEM of a normal foot bones, includes modeling of ligaments and cartilage. The mechanical properties remained constant for the cartilage, bone and soft tissues of the foot and they were attributed as linear elastic, isotropic and homogeneous. This study focused on analysis of bones under dynamic loading (Fung, 1994; Jacob et al., 1996).

In 2001, Bandak and colleagues designed human ankle joint model for the FEM analysis to study impact injury mechanism. Model was developed using medical imaging to represent the anatomical realistic bone geometry included the major ligaments of the ankle. In this model axial impulsive loading was assigned to plantar surface of the foot. According to results the calcareous experiences the highest stresses.

In 2003, Chen et al. , using finite element model investigated the plantar stress distribution under the effect of total contact insoles.

In 2005 Cheung et al., using the same finite element model to evaluate the effect of material stiffness on stress distribution and plantar pressure confined in the foot during balanced standing. This model includes 26 foot bones with distal leg bones tibia, fibula and 72 major ligaments and plantar fascia. The preliminary purpose of this evaluation was to predict von Misses stress in bones, plantar fascia strains and the foot support interfacial pressure.

In 2005,Kasturi et al. used both laboratory tests and empirical simulation to evaluate the mechanical conduct of whole body while the parachute landing fall (PLF) occurs so, as to minimize foot related injuries. Finite element based ellipsoid model was used to evaluate stress distribution under different parameters. Results showed the effect of different parameters including increasing velocity, weight of body, ground type and terrain slope effects force distribution.

In 2009, Cho et al. studied a 3D coupled foot-shoe finite element model to analyze the reciprocity between the foot and the shoe and to predict the effect of such interaction on stress distribution within the foot. Numerical experiments were verified by comparing it with experimental results. Main purpose of study was to analyze effect of sports shoes on stress distribution under impact landing.

In 2010, Yaodong Gu performed experimental as well as Finite element analysis of foot under static loading in balance standing position and Plantar flexed landing position and reported stress distribution in metatarsal bones of foot. Further, stress distribution in footwear was also addressed and validated.

In 2015, Julie et al. reported experimental studies on Parachute landing fall techniques followed by paratroopers for different landing velocities, height and foot postures. The study presented evidence-based guidelines to minimize injuries associated with landing . These all were experimental results.

In 2015, Behzad et al., developed three- dimensional finite element model of foot and sport surface studied force reduction parameters in various sport conditions. However, foot bones were not segmented separately , overall peak force distribution for both sport surface and foot were presented.

In 2016, Wong et al. , focused on injury pattern and fracture mode within foot in case of high energy trauma .The axial compressive impact at 5.0m/s was simulated which affected tarbecular bone in both calcaneus and talus, asserted by shear and compressive forces. This study focused only on calcaneus and talus bone.

In 2017, Niu et al. tried to figure out the effect of forces on muscles and joints in lower limb during dropping height landing. It was a experimental based study performed using sensors on foot for low height jumps and landing. The primary focus of this study was to predict activation of muscle at the time of landing and forces that each in lower limb region contributes.

CHAPTER 3: METHODOLOGY

Overview

This chapter presents the strategy and techniques adopted to gain insights into the mechanism of a stress distribution in foot due to low velocity impact landing. The chapter has been divided into three major sections. Starting with the specification of medical images; reconstructions of models through segmentation from CT images are presented. This is then followed by mesh generation. Numerical simulation of foot in balance standing position and in three different postures during landing for stress measurement.

Workflow

The overall research plan is shown in figure 3.1

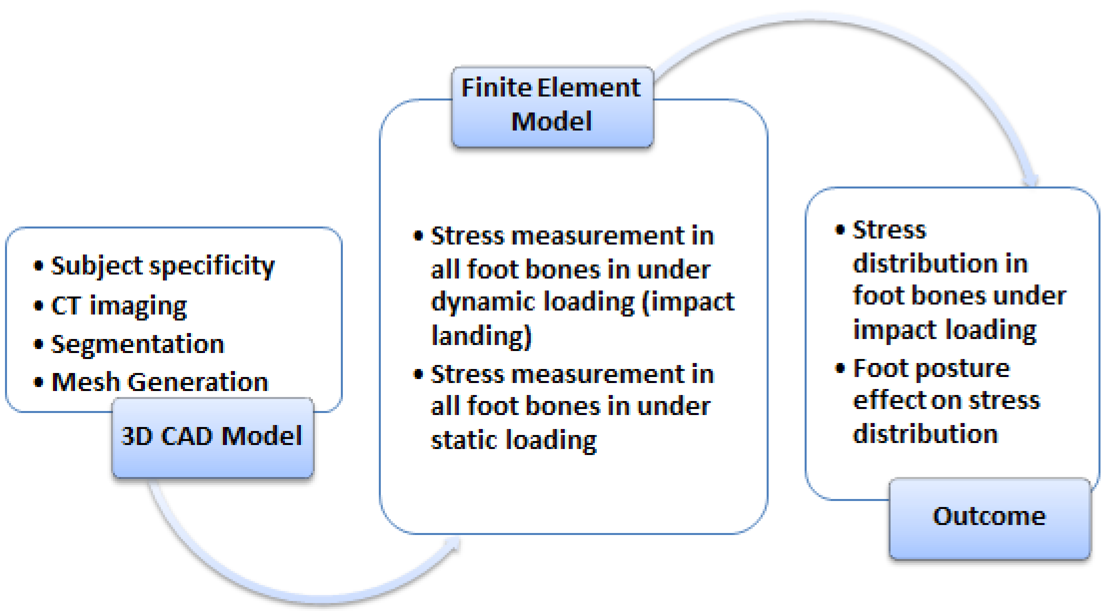


Figure 3.1: Work Flow

3.1 Image Based Modeling

3.1.1 Computed Tomography (CT) scan based Data Acquisition:

Finite element modeling starts with the first step to represent the geometry of footeither can be two-dimensional (2D) or three-dimensional (3D) in the computer, with several ways to achieve.
CT scan of foot generates internal structures which are presented in form of x-ray "slice", which is recorded then on a film. This image recorded is called a tomogram.
CT scan is aprocedure in which x-ray based images are emanated which provides view of internal structures. These images are initially a pixel map of the attenuation coefficient linear X-ray of anatomical structures. The values of pixel are scaled according to the type of structure, whereas scale is called as Hounsfield scale.
The value of intensities for some biological tissues in Hounsfield units is presented in the Figure 3-1. Thus the various bony structures inside the human body, embedded within the soft tissues can be identified using image analysis.

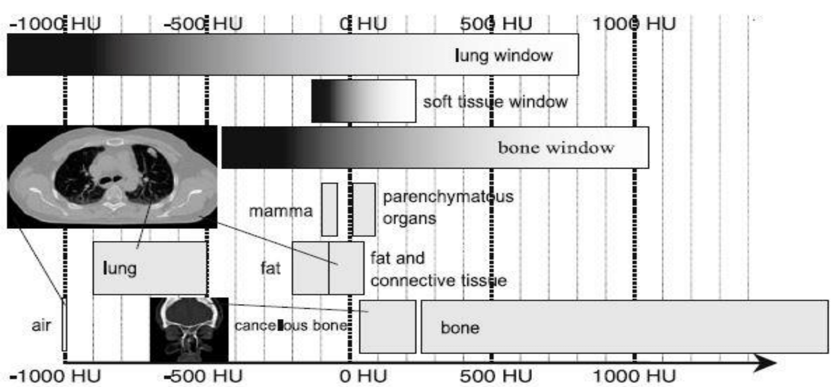


Figure 3.2: Human body tissues intensity scale in Hounsfield units

Following the explanation about the CT technique ,model was constructed based on normal human foot whereas data was obtained from Pims hospital. The datasets are foot scans and of CT modality. Dataset consist of 225 CT slices and acquired in Optima GE Health Care CT 540 scanner.

Figure 3.3:a-Computerized Tomography Scanner,b-scanning of normal patient wearing prosthesis for neutral unloaded position of foot.

Normal foot scan is of a 26 year old female weighing 70 kg. The subject has no clinical history of foot instability, any neurological or musculoskeletal disorders. CT images were taken for the foot in neutral unloaded position with resolution of 1mm pixels per mm. Scans are in dicom format with coronal, axial and sagittal plane.

3.1.2 Segmentation and Model Reconstruction

Foot bones were segmented using Mimics Materialise 21. Segmentation was done based on Hounsfield units (HU). The thresholding operation based on the grey scale using Hounsfield units, separates each bone from other structures and to generate the solid geometry.

Yaodong Gu (2010) defined an interval range of (2342,250: upper limit, lower limit) HU for covering both trabecular and cortical bone of the foot bone structure within CT scans. So the interval we have defined is(2342, ≤200) HU to segment bone from cartilage, skin and soft tissues. Following this procedure, the bone structure in slice can be clearly separated from the surrounding tissues .

The split mask operation was applied in order to segment each bone separately. This geometrical separation was achieved so that the adjacent masks may not connects with any residual pixel.

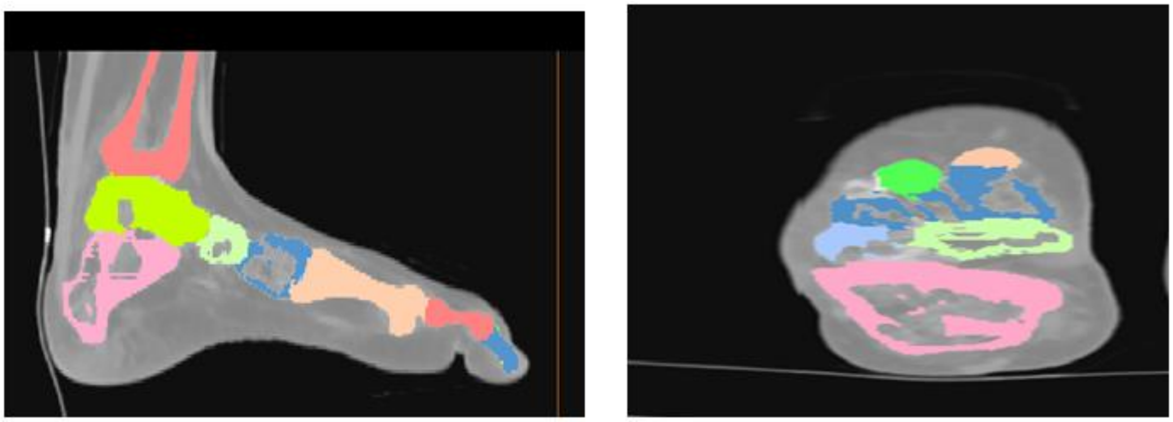


Figure 3.4: examples of split mask technique to separate adjacent bones

Smart fill operations were performed for eliminating the voids at the density masks to obtain independent and smoother primary models.

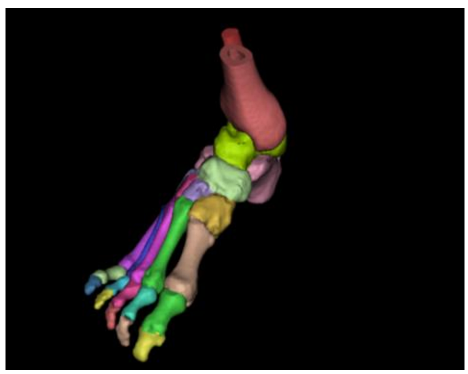


Figure 3.5: Foot bones segmented using split mask method.

3.1.3 Mesh generation and Mesh Convergence Analysis

The segmented models were imported in 3matic and a smoothing filter needs to be applied so, model surface become more regularized. Other filters applied are listed in table 3.1.

To test whether further increase in mesh size will affect the results or not, mesh convergence was carried out using varying edge lengths. Mesh size and their respective edge lengths are shown in table 3.2.

The geometry was then exported into INP file for analysis in Abaqus.

Table 3-1: Manual and Automatic Operation performed to generate the mesh.

Operations Performed	**Function**
Smooth Filter	Factor 0.3
Automatic Fixing	Optimize the mesh
Manual surface mesh tools	Refine single element
Remesh	Transform bad quality triangles into equilateral triangles
Uniform Remesh	Target triangle edge length 3,5, 8 ,12
Quality Preserving reduce angles	Shape quality threshold 0.3000
Volume mesh	Different element size used
Adaptive Remeshing	Improve surface mesh locally
Alignment	Forefoot bones were aligned using translational and rotational mode

Table 3-2: Mesh Convergence Analysis

Models	Components	Edge length	Total elements
1	Foot bones	3	21314
2	Foot bones	5	18548
3	Foot bones	8	16277
4	Foot bones	12	11361

3.2 Numerical Analysis

Numerical methods are those problem solving techniques which are generally used to solve extremely complex real world phenomenon where higher degree of non-linearity is involved. Complicated problems like interaction between bones and deformation in bones due to inertial forces as well as reaction forces under velocity and other parameters are solved through these numerical methods. To get an accurate and better understanding of these intricate systems it is no longer possible to ignore the boundaries between different physical domains.

3.2.1 Structural Analysis

Numerical Analysis is divided into two approaches. First, foot model was validated against static loading while landing of foot in three different postures under velocity is presented in the later part. Both parts are described in detail.

3.2.2 Static Loading (Balance standing)

ABAQUS was used for the finite element analysis of foot bones under static loading. All 28 bones were imported into Abaqus.

3.2.3 Material properties of the different foot structures

It is difficult to select the biological material properties for anatomical models, as most often it depends on the loading condition (Gefen et al., 1999). The materials properties used must balance the prediction accuracy required and the efficiency of the use of the computational resource and time. All the material constants were listed in Table 3.3. All the data were selected from established literatures. In this work, the bones were treated as an elastic materials, the Poisson's ratio and young's modulus are assigned as 0.3 and 7300MPa respectively whereas, density for all bones is 4.49e-10 kg/m^3(Gefen et al., 2000).

Table 3-3: Material properties

Component	**Young's Modulus (MPa)**	**Poisson's ratio**	**Element Type**
Bone	7300	0.3	Tetrahedral solid
Plantar fascia	350	0.4	Axial wire connectors

3.2.4 Loading and boundary conditions for static loading

For validation of foot model, loading and boundary conditions applied were same as reported in literature. It is require to first define interaction between bones as for load transmission. Tie constrain was applied for contact definition between bones. As CT scan data acquired was in unloaded neutral position for foot so as to minimize interactive movement between foot bones.

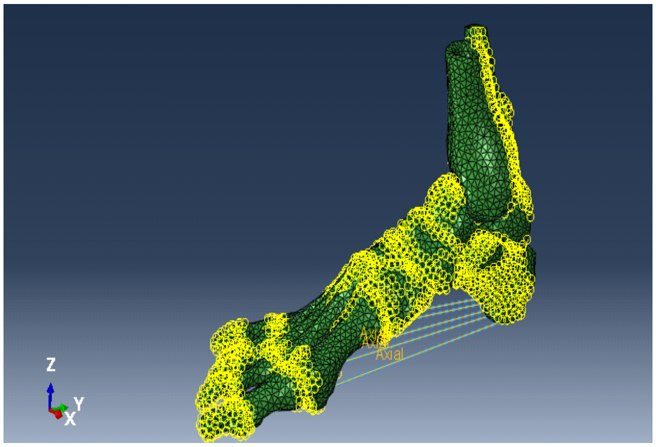


Figure 3.6: Tie constrain defined between all bones and Plantar Fascia designed using axial wire connector elements.

For static loading, dynamic implicit solver was used whereas method applied was Quasi static. It was a nonlinear analysis in Abaqus. The end of the distal surface of the tendon , which is posterior extreme of calcaneus, is a place where Achilles tendon force is applied. However, it is not easy to measure the value of the Achilles tendon force experimentally .

The assumption about Achilles tendon load are reported, according to which it is approximately (1/2 to 2/3) of the body weight applied on the foot. Simkin (1982), in his study calculated the force provided by achellis tendon which is approximately 50% of the body load during standing (Cheung et al., 2005; Gefen, 2000).

The concentrated force of 175 N can be applied through five equivalent vectors on point of attachment of Achilles tendon on calcaneus bone. The load in the form of total force, applied on tibia is 350 N which is half of body mass 70 kg.The plantar surface of foot, that is in contact with ground is fixed in all degrees of freedom(DOF) because of its contact with ground.

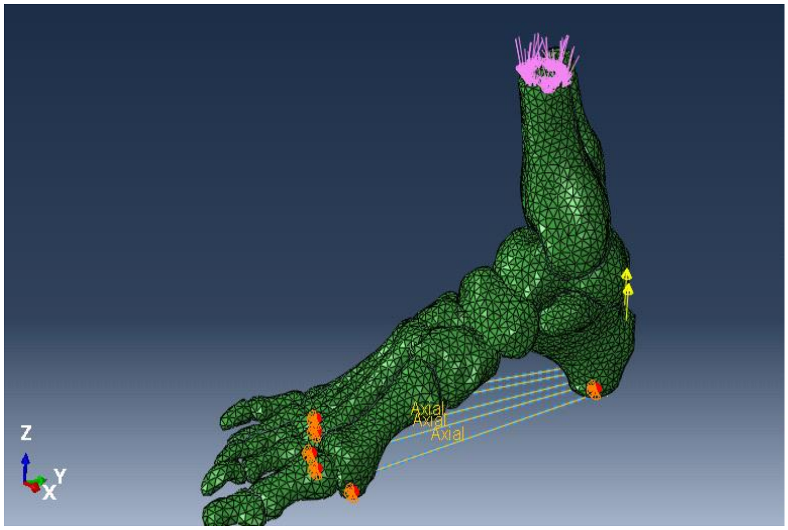


Figure 3.7: Loading and boundary conditions defined

These conditions were for tibial reaction forces. For ground reaction forces tibia and fibula are fixed in all degrees of freedom while ground is defined as rigid body with young modulus of 20000MPa and Poisson's ratio 0.1.The interaction between ground and foot was defined using general contact with friction coefficient of 0.6, by defining reference point on ground. In this case 350 N vertical reaction forces are applied on reference point, while the boundary conditions are applied at the reference point where load was defined, it allows the ground movement in the vertical (upper) direction only.

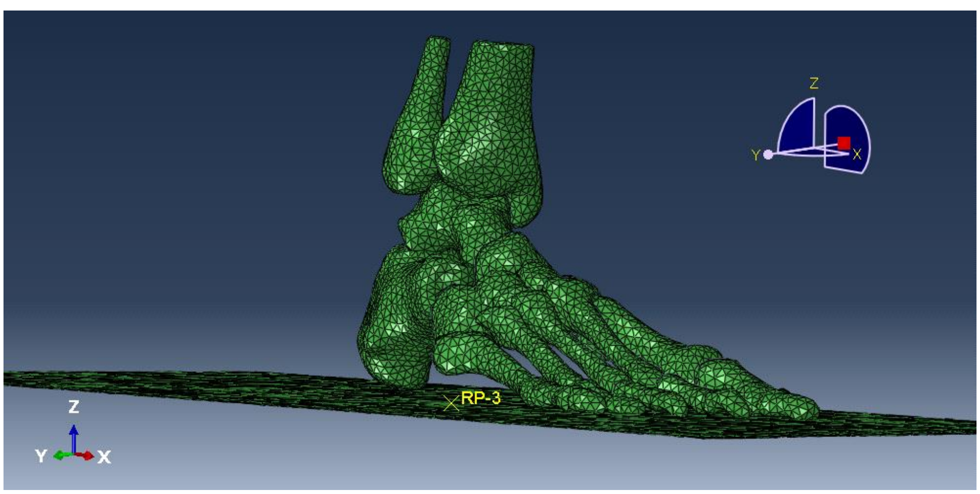


Figure 3.8: Contact between foot and ground defined using Reference point.

Due to complex structure of biological systems, the modeling results seems to be sensitive with the size of the elements used. The element size has to be sufficiently small to produce accurate results, in the meantime, over meshed models should be avoided, which may cause significant waste of computer resource and degrade the efficacy of the analysis. In this work, the mesh size has been systematically varied and the effect of mesh densities on the deformation foot positions was studied. The average mesh size of the model was decreased from 12mm to 3mm. It clearly shows that, with reduced mesh size (e.g. mesh 3) of the foot model, the results become less sensitive to the mesh density. So for current study mesh size 3mm was used.

3.2.5 Loading and boundary conditions for velocity based impact loading

For the second part of study validated model against balance standing position was used. Numerical analyses against three foot postures were to be considered; Flat foot, Plantar flexion and dorsiflexion. These postures were aligned in Matic software using rotational and translational tool and flexion defined was up to 10° degree. This was a Transient fidelity based analysis where there is short increment time as in dynamic explicit.

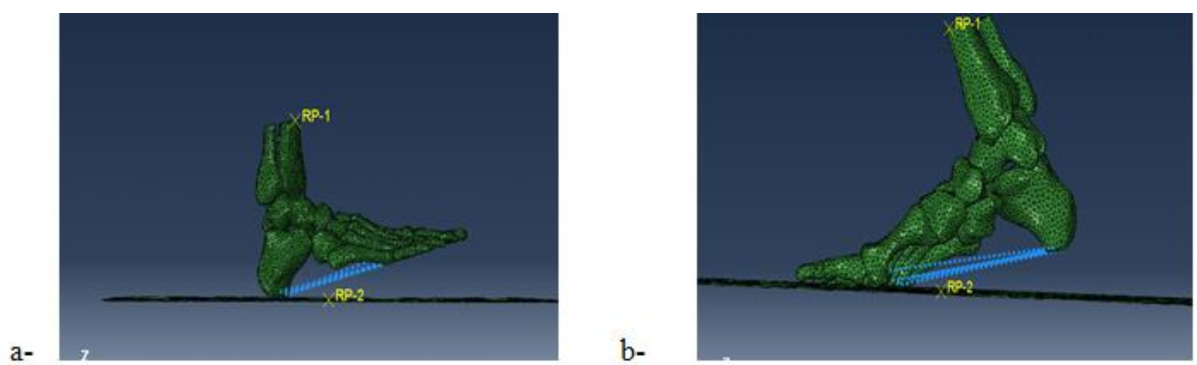


Figure 3.9: Inertia is defined on RP-1 for both cases a- Dorsi flexed foot b-Plantar flexed foot

Then these models were imported into Abaqus and material properties and contact definition between bones were same as for static loading whereas velocity defined to whole model was 4.26m/s using predefined fields for boundary conditions defined according to postures. Inertia of 0.03 kgm^2 was applied on reference point defined on tibia(as for the case of tibia reaction forces).

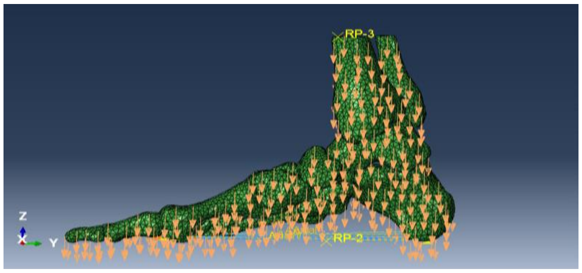


Figure 3.10: Velocity assign to whole flat foot model

Impact loading for velocity 4.26m/s was defined to three foot model cases: Flat foot, Plantar flexion and dorsi flexed foot so as to evaluate the stress distribution for different foot postures.Table 3.4 describes details about loading and boundary conditions.

Table 3-4: Loading and boundary conditions applied on foot

Cases	**Conditions**
1- Flat foot	BW/ inertia 0.03 kgm2 , Achilles tendon force175N ,BC on metatarsals and calcaneus points where they are in contact with ground in U1=U2=U3=0 ,velocity on whole model 4.26m/s ,transient fidelity analysis
2-Planar flexion	Model was ~10 degree plantar flexed Same loading conditions BC on points of metatarsal and phalanges in contact with ground
3- Dorsiflexion	Model was ~10 degree dorsiflexed with same loadingconditions whereas BC only on calcaneus contact point with ground

As mentioned in table for case 1 , which is flat foot model plantar surface was given boundary conditions all degree of freedom. For case 2 ,plantar flexion model only phalanges were given

BC in all degree of freedom and then for Dorsi flexion model , only heel area was given boundary condition as it is in contact with ground. The models were then simulated to results.

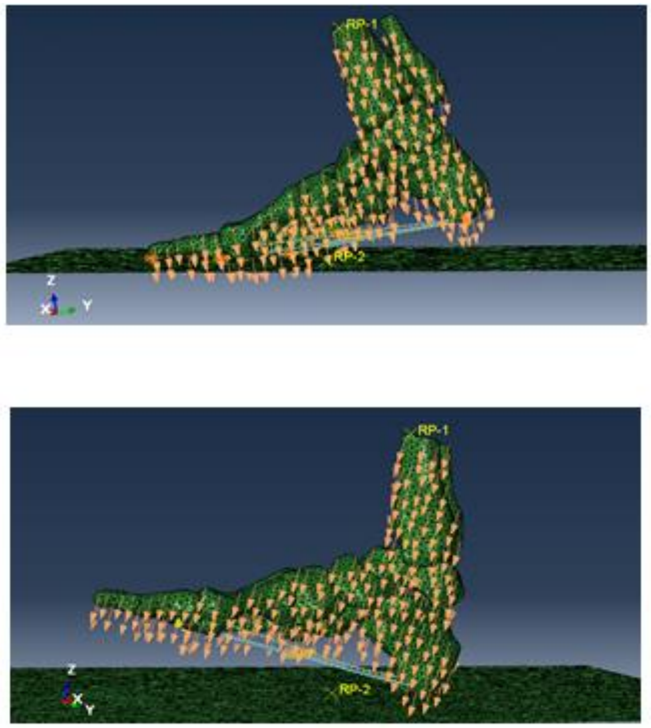


Figure 3.11: Impact loading conditions applied on Plantar flexed and Dorsi flexed foot.

CHAPTER 4: RESULTS

In this study analysis of Finite element is carried out to simulate the mechanical conduct of foot bones in response to static loading and dynamic loading. The primary focus is to analyze the stress-distribution in foot bones in response to loading and reaction forces. First part of this study represents results against static loading for model validation purpose, then results for low velocity landing are represented which shows high stress distribution in plantar flexion pitch.

Results are presented in von Misses equivalent stresses (σ v. M), which will weight the effect of all principal stresses (σ^1,σ^2,σ^3) according to the relation:

$$\boldsymbol{\sigma\ v.\ M=\{½[(\sigma^1\sigma^2)^2+(\sigma^2\sigma^3)^2+(\sigma^3\sigma^1)^2]\}½}$$

The von Misses equivalent stresses, is commonly used as a indicator of stress level in biomechanical research. As shown in the figure, during balance standing, relatively high stresses were predicted at ankle bone and metatarsals. The calcaneal-cuboid joint together with subtalar joints sustained the high stresses. The values of stresses were in reasonable compatibility with some published works (Gefen et al., 2000,· Cheung et al., 2005).

4.1 Image Based Modeling Results

Image processing phase is further divided into sections as described below:

4.1.1 Data Acquisition

Data was acquired, as illustrated in chapter 3 section (3.1.1). The figure 4.1 shows the result of acquired data where bones can be separately distinguished from surrounding tissues.

Figure 4.1:shows a- coronal b- sagittal and c- axial view of foot.

4.1.2 Segmentation and model Reconstruction

Figure 4.2 (a-e) is illustrating the step wise segmentation of foot bones. As defined in chapter 3 (section 3.1.2) segmentation process was followed to obtain the geometry of foot bones.

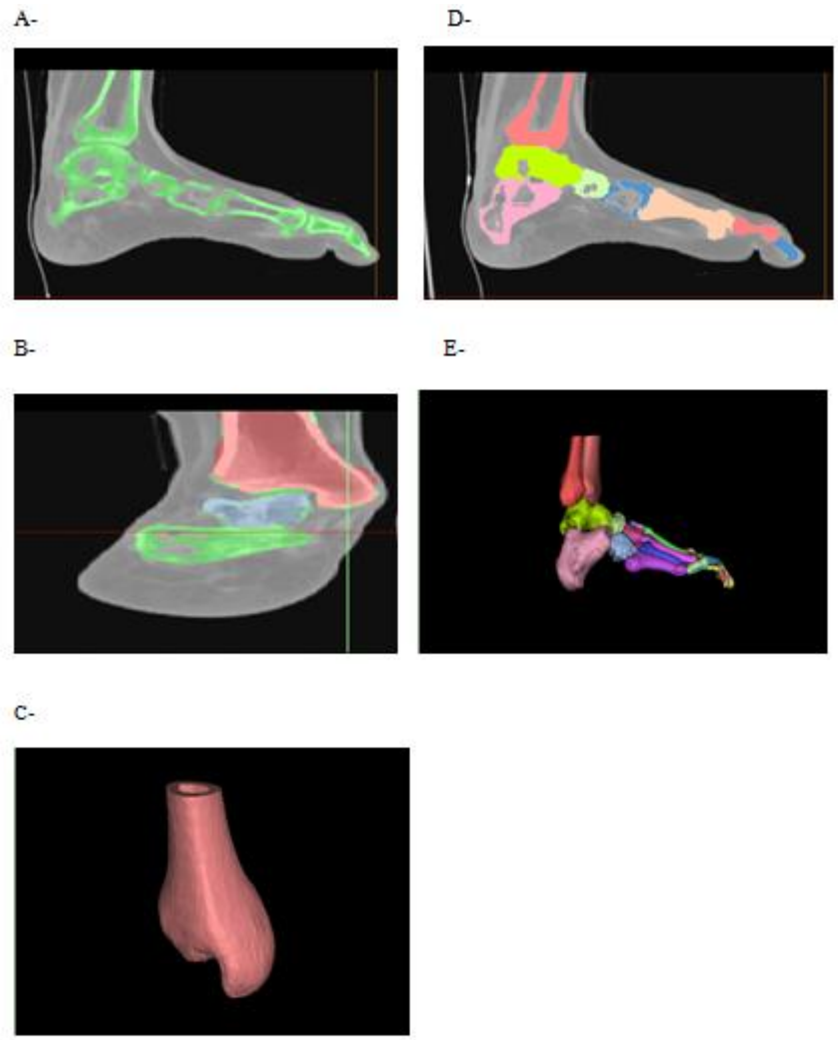
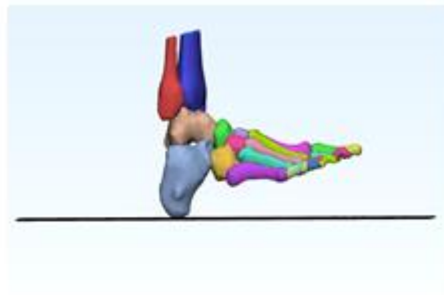


Figure4.2:A- thresholding B- split mask C- Tibia segmented using mask technique D- Mask on all bones E- Foot bone geometry.

A-



B-

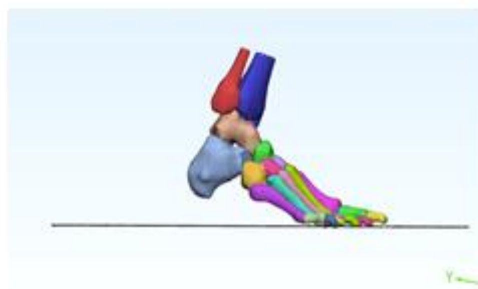


Figure 4.3: Foot bones align in Matic to define: A- Dorsi flexion and B- Plantar flexion posture.

4.1.3 Mesh Generation and Mesh Convergence Analysis

Figure 4.5 is showing the segmented volumes and meshes of the models used for Finite element analysis.

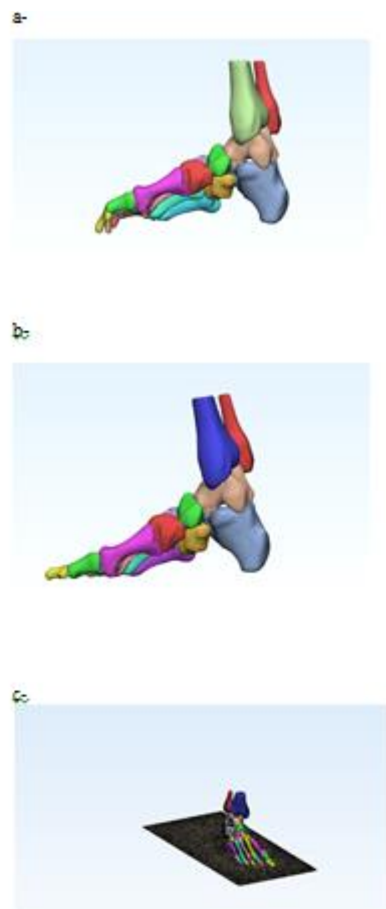


Figure 4.4: a- Model imported to perform meshing b- Bones aligned using translational and rotational command c- Ground extruded and aligned with foot

The mesh operation applied on foot model in represented in Figure 4.5.

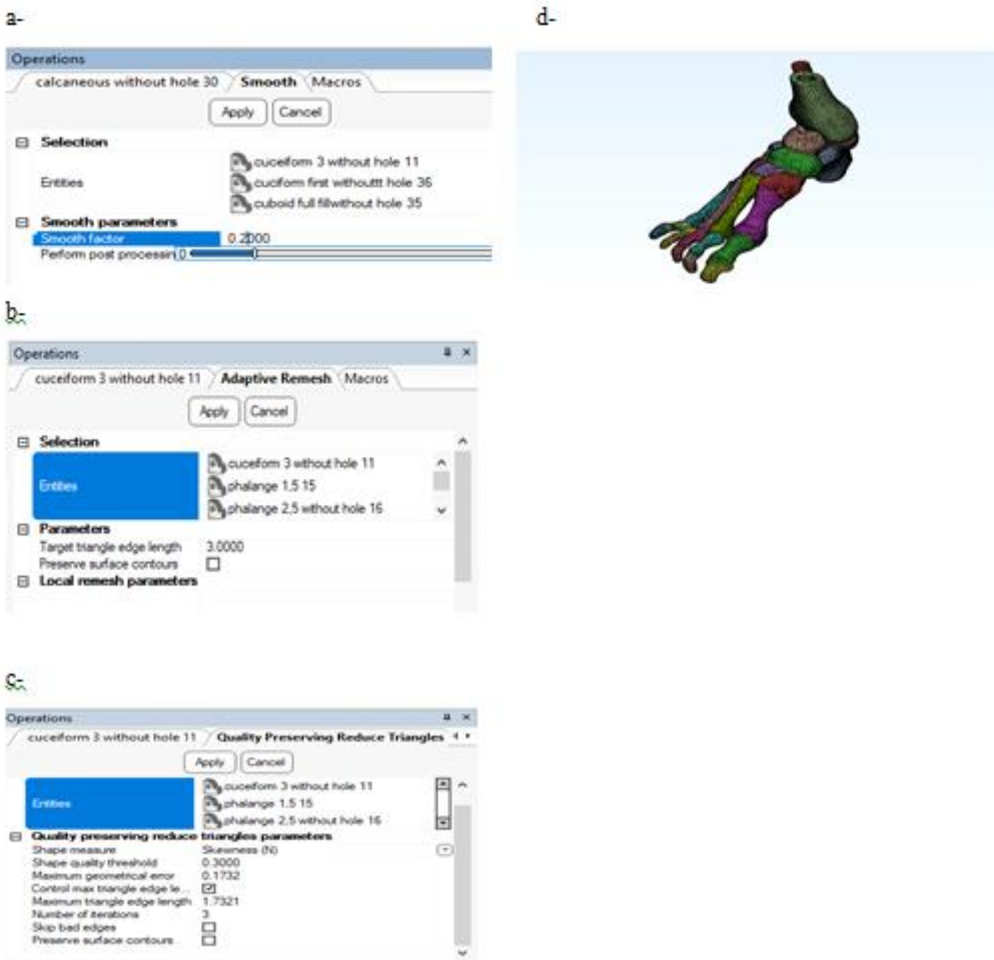


Figure 4.5: a- Smoothing factor of 0.2 is applied on foot bones b- Adaptive Remesh operation performed c- Quality preservance remesh operation performed to reduce bad triangles -Meshed model of foot. d- Mesh results

Figure 4.6 is representing different mesh size models to access mesh convergence.

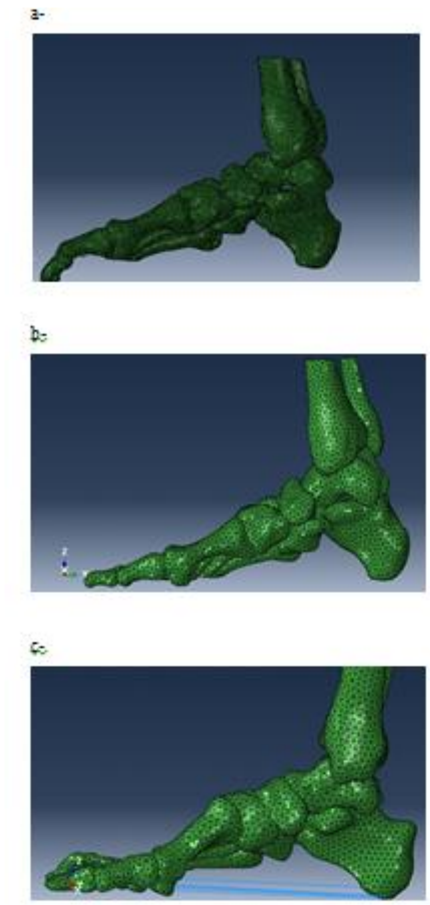


Figure 4.6:a- Edge length 3mm b- Edge length 5mm c- Edge length 12mm

Results are more accurate with the finer mesh. To attain that precision mesh convergence was carried out.

The graph in Figure 4.6 is explaining the relation between mesh density (of four models with different edge length) and stress distribution. Hence the model with edge length 5mm (having 21314 total elements) is the converged one, which is used for the current study.

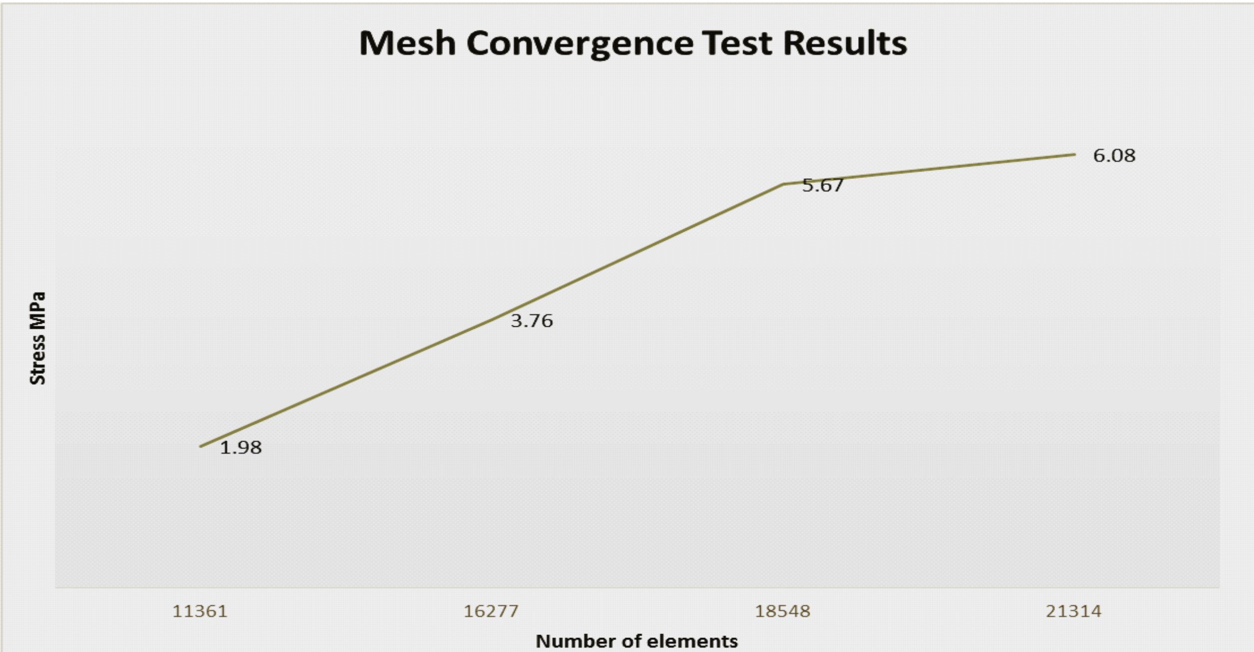


Figure 4.7: Mesh convergence graph

4.2 Numerical Analysis Results

In this section simulation results of foot models under dynamic loading are described.

4.2.1 Stress Distribution for Static loading

As it was a nonlinear analysis, under static loading for balance standing, maximum stress was observed on heel bone, calcaneus and 3rd metatarsal. Stress distribution for foot bones are mentioned in table which are similar in trend with reported literature results.

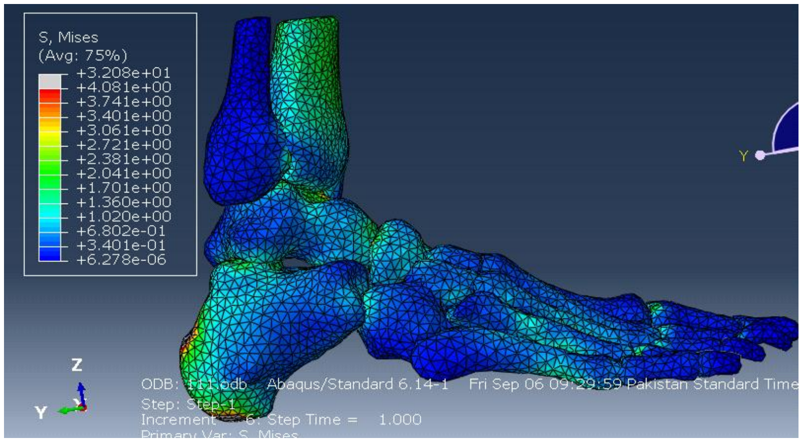


Figure 4.8: Results for static loading

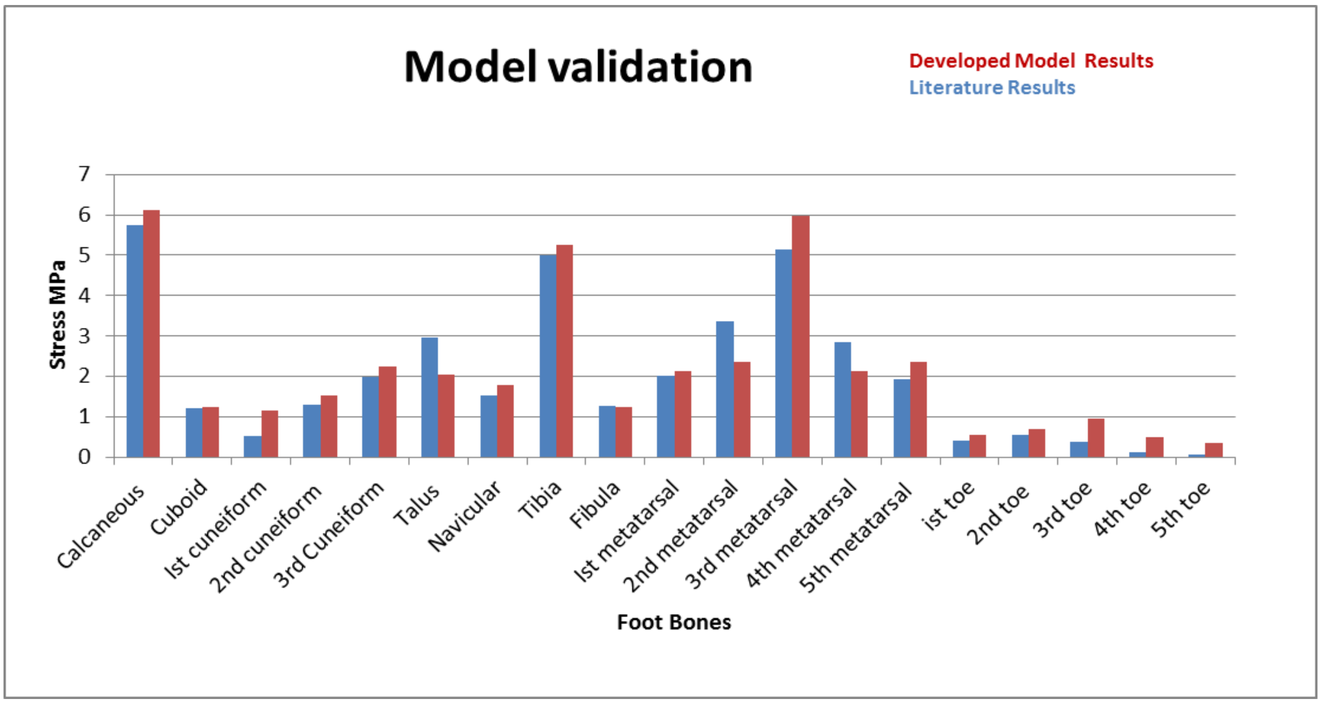


Figure 4.9: Graph validating developed model against literature results

Model developed was validated against reported results where peak stress value was observed on calcaneus bone and 3rd metatarsal bone whereas all other bones followed same trend. Minimum stress distribution was for phalanges.

4.2.2 Stress Distribution for low velocity loading

In current study, three postures of foot under velocity impact were observed flat foot, Plantar flexion and dorsiflexion. This study predicts high stress value for ankle bones under velocity impact in all three cases whereas Plantar flexion posture exposes foot to absorb maximum reaction forces upon contact with ground. The stress distribution for each bone of foot in Plantar flexion pitch is observed high.

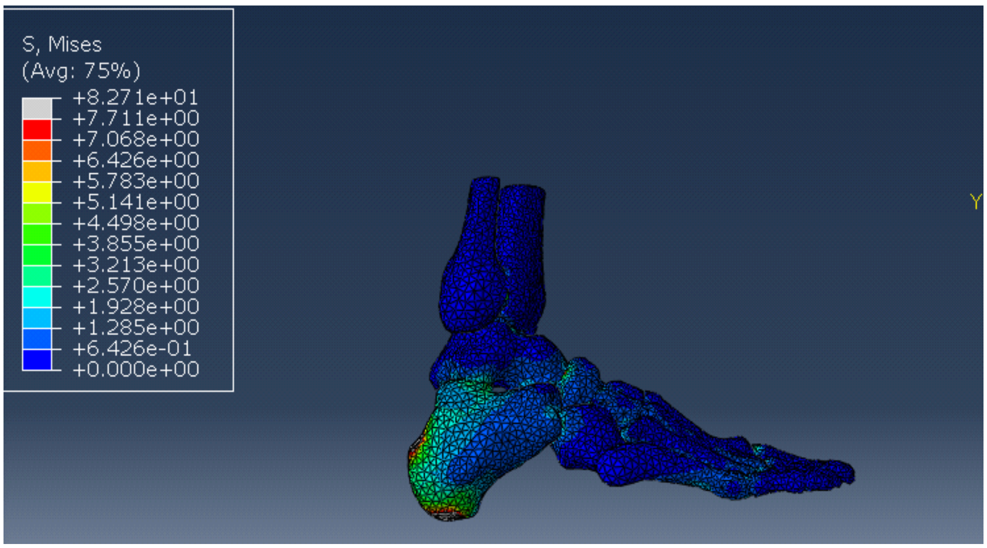


Figure 4.10: Case 1 results

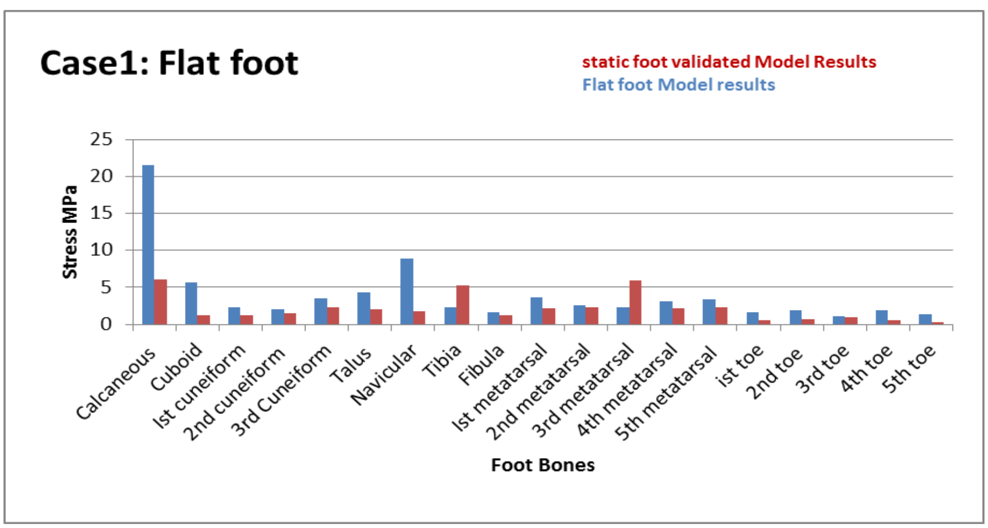


Figure 4.11: Graph on comparison between developed model case 1 and validated model.

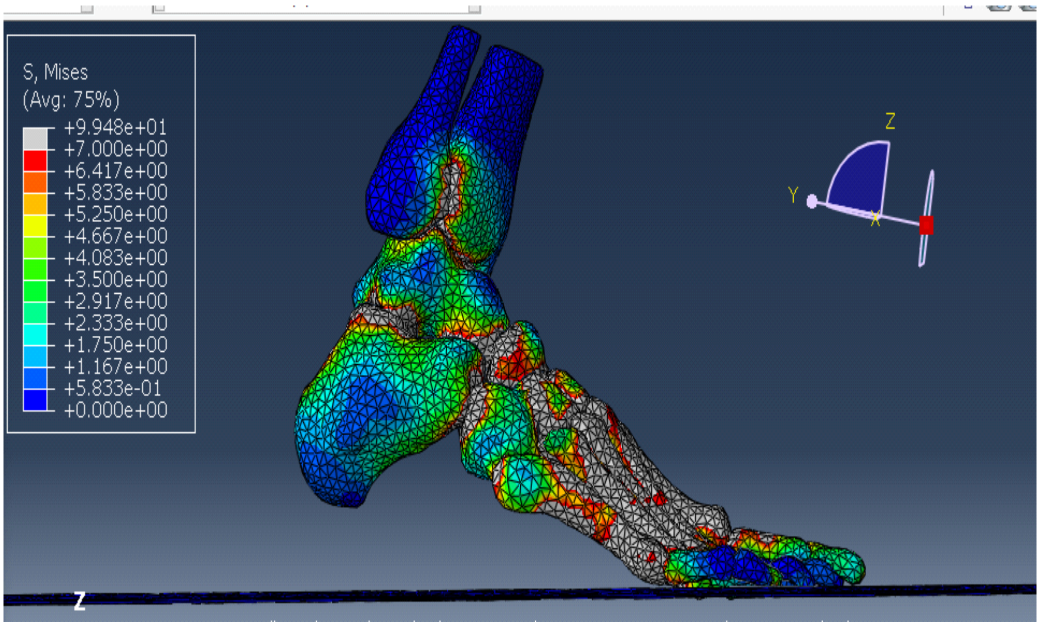


Figure 4.12: Case 2 results

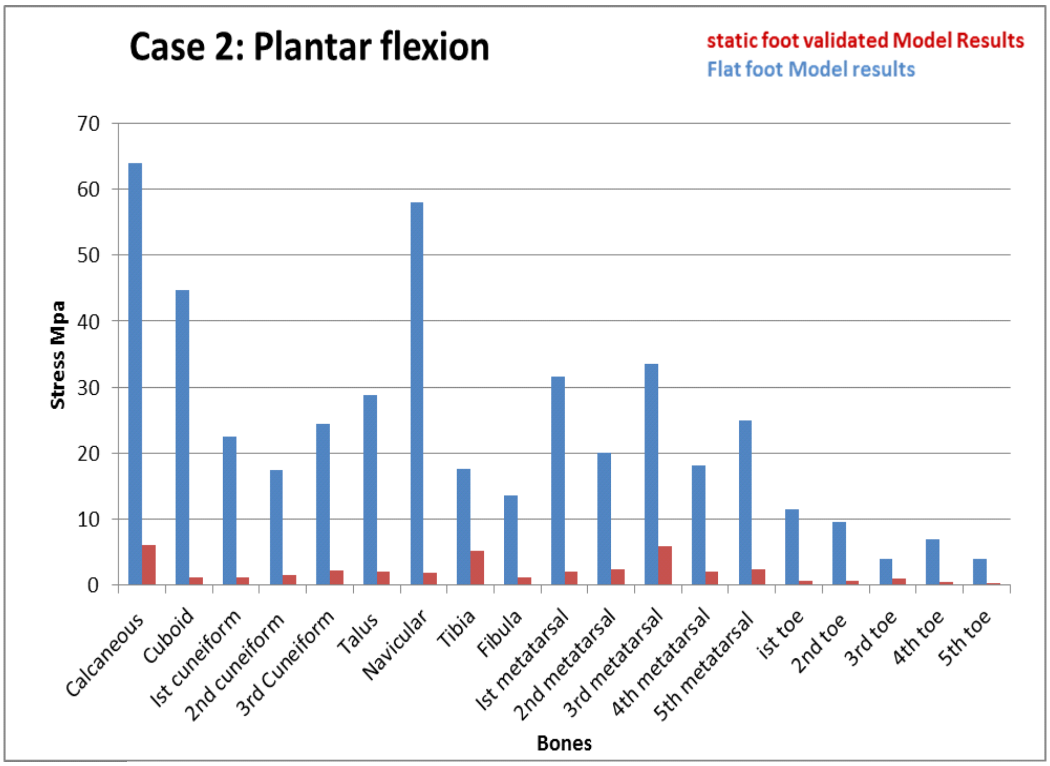


Figure 4.13: Graph on comparison between developed model case 2: Plantar flexion and validated model

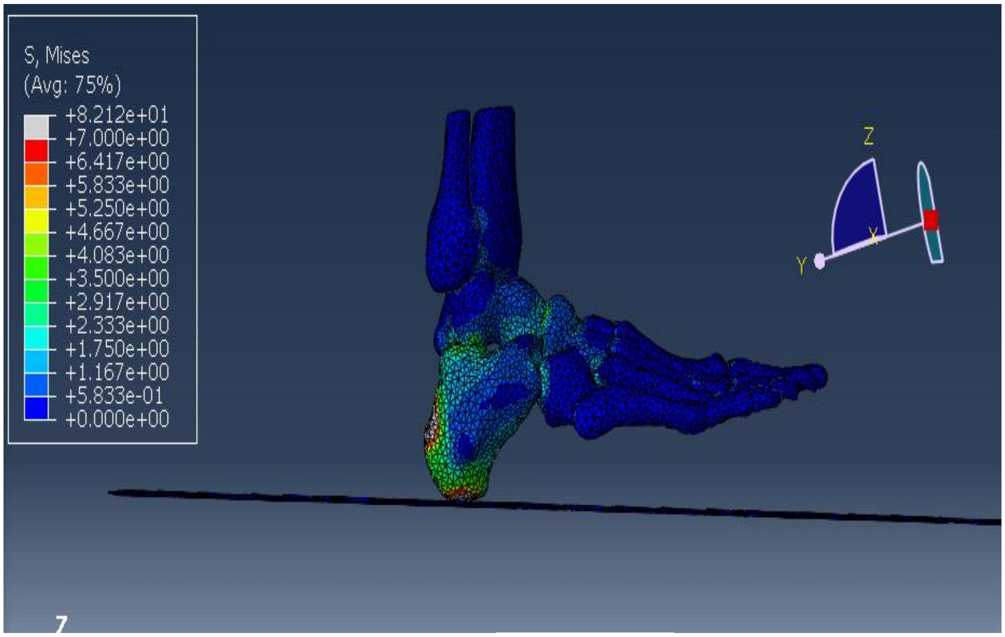


Figure 4.14: Case 3 results

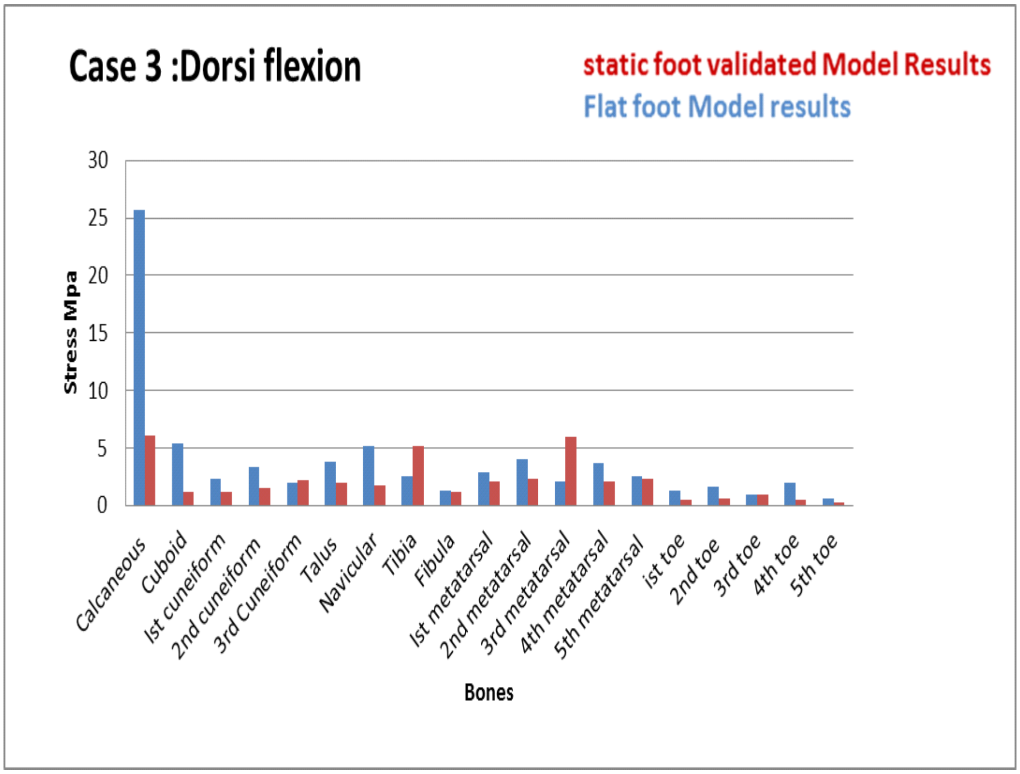


Figure 4.15:graph on comparison between developed model case 3; Dorsiflexion and validated model.

CHAPTER 5: DISCUSSION

Both FE analysis and biomechanical experimental techniques are required to study biomechanical behavior of the foot, whereas experimental investigations could provide only clinically relevant data like fractures and injuries with regards to different foot conditions. Such studies were not able to present the internal stress states of foot structures whereas computational model makes it a valuable tool to perform such tasks.

Once it was verified by experimental data, models could offer detailed information and predict the effects of some key variables as shown by previous works of FE modeling of the lower limb system (Tao et al., 2009; Goske et al., 2006; Gu et al., 2005; Barani et al., 2005; Erdemir et al., 2005; Chen et al., 2003; Lewis, 2003; Syngellakis et al., 2000; Lemmon et al., 1997; Chu and Reddy, 1995; Shiang, 1997).

However, there have been very limited detailed studies of foot based FE modeling to evaluate the foot internal structure response during different foot landing postures.

Balance position of standing for the foot not speaks for complex loading that usually foot experiences in real world. It becomes obvious to examine the mechanical conduct of foot internal structure during different foot movement. Loading can be a common factor associated with many foot injuries during parachuting (Gruneberg et al., 2003; Willems et al., 2005).

In current work, this challenging and important problem has been successfully investigated through subject specific FE modeling. Developed finite element model of foot based on subject specified dimensions and materials properties, provides with detail study on human foot bones impairment. The numerical results of developed model are compared with literature results for balance standing position which were validated against reported biomechanical tests, used for the validation and maintaining of FE models under prescribed conditions .The validated model can then be used to achieve objectives and to obtain the quantitative evaluations of the internal deformation of the foot structures under impact based loading.

Fracture and foot bones dislocation are the most common foot injuries, some of these are associated with the foot pitch during impact (Ekrol and Court-Brown, 2004). The metatarsal, navicular, cuboid, talus and calcaneus bone are more prone to absorb the stress and predominant sites of stress fracture, as the heel bone is major bone which absorbs reaction forces generated from ground. So, the present study predicted stress distribution in foot bones, which seems to be significantly different in case of both normal and flexed landing conditions.

Results showed that the peak stress could directly affect ankle injuries. The stresses level in the calcaneus , navicular ,Talus, and cuboid bone was the highest among other bones under the normal landing condition while for Plantar flexion high stress value for calcaneus , cuboid , navicular , 1st and 3rd metatarsal bones .This is the posture of foot which causes the foot to take up the large percentage of the impact forces . Research findings also indicate that 1st and 3rd metatarsal to be most injured among other metatarsals (Weinfeld et al., 1997).

For Dorsi flexion, calcaneus bone showed maximum stress value.

CHAPTER 6: CONCLUSION AND FUTURE WORK

The 3D detail geometric model of human foot Based on CT scan data is elaborated to evaluate the distribution of stress. The strain and stress trend in the bone under low velocity loading conditions and balanced standing position was estimated.

Current study was to determine the localized stress distribution in the foot bones under low velocity impact landing in different postures which are observed commonly during paratroops landing. The model was first validated and then predicted results of mentioned objectives.

FEM model developed using axial wire connector elements and tie constraints, successfully predicts stress in foot bones at balance standing position. This methodology is superior to contact methods due to more stable numerical solutions.

Homogenous and nonlinear elastic material properties were assigned to the models. This approach probable thereal situation. CT scan of foot I neutral unloaded position was acquired to minimize bone to bone movement.

Dynamic implicit solver also provides good stress prediction comparable to dynamic explicit solver for stress field in foot. This saves on computational time and resources.

Flat foot position landing shows that maximum stress concentrates in ankle region and less stress in metatarsals. An increase of 2-3 times in maximum stress +8.271e+01 is also found in this case.

Landing in plantar flexion predicts maximum stress concentration in ankle region and metatarsals however maximum stress is +9.948e+01. This shows calcaneus, cuboid, talus, navicular, 1st and 3rd metatarsals are more prone to fracture during this case of landing.

Landing in Dorsi flexion predicts maximum stress concentration in ankle region and 2nd metatarsal however maximum stress +8.212e+01.

The main goal of this study is to predict the stress distribution. However other interesting studies could be possible by involving the structures only so as to further enhance the design of proper foot boot model in future and to improve the parachute landing fall technique.

Limitations of study are as under:

Muscles, skin, ligaments and cartilage were not considered, so as to simplify the model. Main focus was on bony structures and joints. As Dicom images obtained were not of good resolution, so it was not possible to segment soft parts accurately.

This study focused on Achilles tendon based loading specifically intrinsic and extrinsic muscle forces. Forces other than this were excluded thereby preventing correct force application and results in specious placement of stress and strain among foot bones.

For impact landing, only low velocity parameter was included which can be expanded by including high velocities as well as studying effect of forces in drop zone during parachute fall.

Foot bones were aligned manually for defining different foot postures which predicted stress values showing same trend followed reported in literature for experimental study , it can further improved or can be validated by acquiring mentioned foot posture scans.

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