Finite element analysis of pin positioning in Lapidus procedure for treating Hallux Valgus

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FINITE ELEMENT ANALYSIS OF PIN POSITIONING IN LAPIDUS PROCEDURE
FOR TREATING HALLUX VALGUS

by

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Bachelor of Technology in Mechanical Engineering
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July 2001

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Biomedical Engineering
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August 2004
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for Treating Hallux Valgus

is approved in partial fulfillment of the requirements for the degree of

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Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

Finite Element Analysis of Pin Positioning in Lapidus Procedure for Treating Hallux Valgus

by

Haritha Royyuru

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Associate Director of Nevada Center for Advanced Computational Methods
Associate Professor of Mechanical Engineering
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A finite element analysis is carried out to find the optimum position of the pin placement of mini fixator in Lapidus procedure in the treatment of Hallux Valgus. Various parameters are considered for analysis like diameter of the pin, positioning of the pin from the fracture site, number of pins effecting the stability of the fixation device and fusion site, rail distance from the fusion site, effect of width and length of the rail, effect of fusion angle and effect of pin angle positioning in fusion the joint by using FEMLAB 2.3 for both modeling and analysis. A 2D model is constructed with the bone joint consisting of first metatarsal and cuneiform along with the fixation device. The dimensions of the model are taken similar to a prototype model of the foot. Static analysis was done to find the displacement between the first metatarsal and cuneiform with the application of the mini fixator.
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CHAPTER 1

INTRODUCTION

1.1 Identification of Problem

Hallux Valgus is a foot disorder consisting of lateral deviation of the proximal phalanx on the metatarsal head. These are often referred as bunions and are treated in different ways. In the preliminary stages, surgery may not be required and are treated by using a small pad under the feet, which gives comfort to the patients. In case of surgery, the most widely used technique is the Lapidus Procedure where the bunions are removed and the cuneiform and first metatarsal head are fused together. For this fusion many techniques such as external fixation devices, immobilization techniques and internal fixation devices are employed to stabilize the fixed bones. External fixation device is the most common one because it aids the patient to walk sooner than other techniques. It also heals the wound quickly because there will be continuous blood supply to the wound when the patients walks than in any immobilization.

However the effect of using fixation device depends on many factors, which is not studied in the literature as per our knowledge. Since the joint is very small mini fixators are used for the study. Our study primarily focuses on examining the principal parameters that Effect the fusion of the joint and identifying the optimal positioning of the device. Parameters considered are the diameter of the pin, pin positioning from the fusion site,
rail positioning from the fusion site, pin numbers, geometric parameters of rail like its length and width and orientation of pins.

1.2 Purpose of Study

As far as now, there is no publication discussing the effect of geometric factors on stiffness of the. This study discusses the Effect of different geometric parameters of the mini external fixation device on the fracture stability for treating Hallux Valgus using Lapidus Procedure. This is basically done because even though the bunion is treated properly, the joint between cuneiform and the first metatarsal is not completely fused. It is observed that there exists a gap at either of the ends of the joint. Since both the cuneiform and metatarsal are not straight planar surfaces and as they are inclined, the joint sometimes cannot fuse properly after the procedure. Placement of the pin horizontal to the surface does not always serve the purpose and as well the positioning of the pin becomes critical in this. Our research objectives are to provide a comprehensive study of major parameters effecting the gap so that the doctor can place the pin effectively in a position that yields the desired gap closing without gaping at farther ends.
CHAPTER 2

REVIEW OF LITERATURE REVIEW

2.1 Hallux valgus disease

Hallux valgus is, often referred to as a “bunion”, a deformity of the big toe (Figure 2.1). The toe tilts over towards the smaller toes and a bony lump appears on the inside of the foot. A bony lump on the top of the big toe joint is usually due to hallux rigidus. Sometimes a soft fluid swelling develops over the bony lump. The bony lump is the end of the "knuckle-bone" of the big toe i.e. the first metatarsal bone which becomes exposed as the toe tilts out of place. Bunions can be considered as hereditary as bunions are a bit common in people with unusually flexible joints. They are also common in women than in men.

Figure 2.1-A foot with Hallux valgus and its Radiograph
Bunions do occur in cultures in which shoes are not worn, but much less commonly. Shoes that squeeze the big toe or do not fit properly, or have an excessively high heel, can probably help to cause the deformity especially in people who are at higher risk anyway. The main problem is usually the pressure of the shoe over the bony prominence, which causes discomfort or pain. Sometimes the skin over the lump becomes red, blistered or infected. The foot may become so broad that it is difficult to get wide enough shoes.

The big toe sometimes tilts over so much that it rubs on the second toe, or pushes it up out of place so it presses on the shoe. Also, the big toe does not work as well with a bunion, and the other toes have to take more of the weight of the body while one walk. This can cause pain under the ball of the foot called as "metatarsalgia". Sometimes arthritis develops in the deformed joint, causing pain in the joint. Many people with bunions are quite comfortable if they wear wide, well fitting shoes and give them time to adapt to the shape of their feet. A small pad over the bony prominence, which can be bought from a chemist or chiropodist, can take the pressure of the shoe off the bunion. If simple measures do not make comfortable, an operation may improve the situation. An operation will not only give an entirely normal foot, but it also correct the deformity of the big toe and narrow the foot back towards what it should be. The severity of Hallux valgus is determined by examining the foot angles anatomically as shown in the Table 1.
Table 1 - Severity of Hallux valgus based on anatomy of foot

<table>
<thead>
<tr>
<th>Severity</th>
<th>HV angle</th>
<th>IMT angle</th>
<th>Incongruent MTPJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>&lt;15deg.</td>
<td>&lt;9deg.</td>
<td>No</td>
</tr>
<tr>
<td>Mild</td>
<td>15-20deg.</td>
<td>9-11deg.</td>
<td>No</td>
</tr>
<tr>
<td>Moderate</td>
<td>20-40deg.</td>
<td>11-18deg.</td>
<td>Yes (unless abnormal DMAA)</td>
</tr>
<tr>
<td>Severe</td>
<td>&gt;40deg.</td>
<td>&gt;18deg</td>
<td>Yes</td>
</tr>
</tbody>
</table>

2.2 Lapidus procedure

There are lot of different operations for bunions, depending on the severity of the deformity, the shape of the foot and whether arthritis has developed in the big toe joint. Most common method to treat Hallux Valgus is the Lapidus Procedure, which is used to treat Hallux Valgus. An orthopaedic surgeon performs the best operation for the patient, depending on the condition of his / her foot. This thesis discusses one of the most common surgical technique called “Lapidus Procedure” which is used to treat this type of foot condition. While performing Lapidus Procedure, surgeon initially uses a bone saw to remove the boney prominence of the first metatarsal head. Then the soft tissue connecting the Hallux, first metatarsal head and the second metatarsal and sesamoid bones are released to prevent the contracture of the big toe. Lastly a wedge bone, which is formed between the first metatarsal and the cuneiform, is removed and the joint is fused. The fusion of this joint is usually performed using Internal or External Fixation devices or using a simple screw to pass through the joint. This thesis discusses the parameters that
effect the placement of the mini external fixator on the gap closing between the cuneiform and first metatarsal joint and optimum positioning of the fixator.

2.3 Problems with surgery

However, an operation cannot make the foot narrow enough to wear tight shoes, nor can it fully restore the strength of the big toe. Research shows that 85% of people who have bunion corrections are satisfied with the results. However, a number of problems can arise due to the following reasons:

- The big toe is usually stiffer than before the operation. For most people this does not matter, but for athletes or dancers it is very important.

- The big toe is slightly weaker with a bunion, and this transfer's weight onto the ball of the foot. After bunion surgery, this transfer of weight can increase. Therefore, if pain persists under the ball of the foot ("metatarsalgia") it may be worse after bunion surgery, and it may also develop for the first time. Careful surgical technique can reduce this risk, but it cannot avoid it completely. Most people who develop metatarsalgia are comfortable with a simple insole in the shoe but occasionally surgery is required.

- In some people the big toe slowly tilts back toward the original position and occasionally this is bad enough to need to have the operation redone. On the other hand, the toe can tilt the other way, though much more rarely. Again, occasionally this is bad enough to need to have the operation redone.
Infections in the wound, plaster problems and minor damage to the nerves of the toe can occur in any foot surgery. Usually these are minor problems that get better quickly.

The above problems unveil the importance, to have any bunion surgery done by a properly trained and experienced surgeon.

2.4 Fracture healing

Although to a large extent biological factors effect the fracture healing, there are mechanical factors at some stage that largely affect the healing process. Therefore two factors effecting the healing are discussed below.

1. Biological Process of Fracture Healing:

The healing of the bone takes place in three phases: 1) inflammation 2) reparation and 3) remodeling. The first phase, inflammation, occurs immediately following the bone fracture. At that time, a hematoma or blood clot occurs at the fracture site. This hematoma provides two important factors important for fracture healing. First, the hematoma provides a small amount of mechanical stability to the fracture site. Second, the hematoma brings osteoblast and chondrocyte precursors to the fracture site in large numbers that can begin to differentiate into osteoblasts and chondrocytes to begin producing matrix that is very important. In addition, macrophages and osteoblasts come into the site to remove damaged and necrotic tissue. Also, since bone fracture usually involves disruption of the periosteum surrounding the bone, more precursor cells from the periosteum will be introduced into the fracture site. This will begin the process of making a fracture callus through the general process of osteogenesis, laying down bone.
on soft tissue. Both types of osteogenesis, intramembranous and endochondral ossification may be occurring at the fracture site. The resulting proliferation of woven bone tissue will produce a fracture callus, bridging the fracture gap. This is shown in Figure 2.2 below.

Figure 2.2-Histology of callus

The second step in the biological fracture healing is the reparation phase. In this phase, the processes of osteogenesis continue and a fracture callus bridges the fracture site. The bone again can be produced through intramembranous ossification, endochondral ossification or both. It is at this stage of fracture healing that external mechanical stimuli can have the greatest Effect on fracture healing. This is because mechanical stability is crucial at this stage of fracture healing. Although it is not necessary to completely immobilize the fracture, and there is some debate about the need for small motion at the fracture site, it is definitely clear that too much motion will lead to
a non-union. A non-union is the healing of a fracture site with soft tissue instead of bone. The desire to prevent non-unions is the reason that different types of fracture fixation devices are used in clinical practice.

The healed bony callus is formed of woven bone and primary bone. At this point, it consists of a large bony bridge connecting the two bones. The base material of the callus typically will have lower strength and stiffness than mature lamellar bone. It is the large mass of bone in the callus that gives the construct its strength. To reduce the callus mass while maintaining mechanical integrity the callus must be remodeled to produce the lamellar bone. During the remodeling period, the large fracture callus is reduced to become the size of the bone at the fracture site. The woven/primary bone is replaced with secondary lamellar bone. This process may take months or even up to a year or more in adults.

2. Mechanical Effects on Fracture Healing:

The premise that mechanical deformation and motion can affect the course of fracture healing has been postulated for many years. In the 1960's it was discovered that rigid fixation of a fracture site could lead to direct haversian bone healing without formation of an intermediate callus. Although the concept that mechanics can effect fracture healing has been around for a while, direct evidence or a mathematical theory relating mechanics to fracture healing has not been rigorously tested. The two main theories relating mechanical stimuli to fracture healing are one due to Perren and one due to Blenman and Carter. The theory proposed by Perren is called the interfragmentary strain theory. It postulates changes in fracture gap tissue related to strain magnitudes in the fracture gap. Perren theorized that the magnitude of interfragmentary strain would determine the
subsequent differentiation of fracture gap tissue. Interfragmentary strain was defined as the relative displacement of the fracture gap ends divided by the initial fracture gap width. This may be written as:

\[ \varepsilon_{\text{gap}} = \frac{\text{Fracture Gap Displacement}}{\text{Initial Gap Width}} \Rightarrow \frac{\Delta u}{L} \]

This definition of gap strain corresponds to a small deformation definition of strain. Perren theorized that interfragmentary strains above 100% would lead to non-union. Strains between 10 and 100% would lead to sustain initial fibrous tissue formation. Strains between 2 and 10% would lead to cartilage formation and an endochondral ossification formation. Strains under 2% would lead to direct bone formation and primary fracture healing. This theory is illustrated in the Figure 2.3 below:
Perren based his ideas on the fact that tissues that were strained beyond their ultimate strain could not form in the gap. In addition to the strain effects on initial formation, Perren believed that once set in progress that once tissues formed they would stiffen the fracture gap, which in turn would lead to lower strains, which would allow formation of the next stiffest tissue and the cycle would repeat until all bone was formed.

Theory from Blenman and Carter's differs from Perren's in that it not only predicts that the magnitude of mechanical stimulus will affect fracture tissue differentiation, but also the type of mechanical stimulus. This theory is actually a subset of a broader theory
developed by Carter and colleagues relating mechanical stimulus to tissue growth, remodeling and healing. In terms of fracture healing, Carter and Blenman believed that vascular supply to tissues was the primary factor determining tissue differentiation. Based upon the level of vascularity, they believed that both the magnitude and type of mechanical stress, basically hydrostatic pressure versus octahedral shear stress, would effect the type of tissue within fracture sites.

All rigorous applications of mechanically mediated fracture healing theories are not common, aspects of these theories can be seen in the use of devices to fix and stabilize fractures. It is widely believed that some mechanical rigidity is needed for complex unstable fractures to prevent gap tissue stresses from becoming too high and preventing bone formation to heal the fracture.

It is intuitive that the mechanical stability at the fracture gap can be achieved using external fixators and the fixator construct stiffness depends upon the geometric configuration of the fixator.

2.5 Fixation device

The following picture shows the fixation device commonly used in Lapidus Procedure.
Procedure for application of the device:

1. The pins are drilled into the bone, using clamp as template. Wire closest to the MTP (Metarsophalangeal) joint is inserted first, in the frontal plane.

2. Place a standard clamp over the wire with dot on cam in line with dot on clamp. Head of cam must face away from bone. Position clamp 5-10 mm from skin and trim this wire (and all subsequent wires) so that 5 mm projects from clamp.

3. Insert second wire either axially (emerges from clamp parallel with first) or transversely (converges with first wire) depending on space available. Use image intensification. Choose appropriate length of Minifixator body and attach one threaded bar to the clamp.

4. Tighten double ball-joint cam slightly and align fixator with the long axis of bone.

5. Attach second clamp and insert second set of wires.
6. Lock clamps to wires by turning cams. Lock one clamp to bar with its locking screw.

First geometric parameters like diameter of pin, length of rail, width of rail, separation distance of the pins and rail are considered for analyzing major factors affecting the fracture stability. By understanding those factors, more sophisticated fixation device can be developed. The second objective is to identify whether, the orientation of the pin in the current device can be changed to achieve proper gap closing with the existing design. The positioning of pins at different distances from fracture site and at different angles was simulated. The effect of fracture gap angle in closing is compared along with the metatarsal is cutting angle. Such cutting inconsistency occurs because no proper device was designed for doctors that can precisely cut the wedge at metatarsal.

2.6 Finite element analysis

In the field of engineering design we come across many complex problems, the mathematical formulation of which is tedious and usually not possible by analytical methods. At such instants we resort to the use of numerical techniques. Here lies the importance of Finite Element Analysis, which is a very powerful tool for getting the numerical solution for wide ranges of engineering problems. The basic concept is that a body or structure may be divided into smaller elements of finite dimensions called as “Finite Elements”. The original body or structure is then considered as an assemblage of these elements connected at a finite number of joints called as “nodes” or “nodal points”.

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The properties of the elements are formulated and combined to obtain the properties of the entire body.

The equations of equilibrium for the entire structure or body are then obtained by combining the equilibrium equation of each element such that the continuity is ensured at each node. The necessary boundary conditions are then imposed and the equations of equilibrium are the solved to obtain the required variables such as stress, strain, temperature distribution or velocity flow depending on the application. Thus instead of solving the problem for the entire structure or body in one operation, the method is mainly devoted to the formulation of properties of the constituent elements. A common procedure is adopted for combining the elements, solution of equations and evaluation of the required variables in all fields.
CHAPTER 3

METHODOLOGY

3.1 Problem Formulation

FEMLAB 2.3 is used for two dimensional analysis as well as modeling. A two-dimensional model of the joint configuration from the first metatarsal and cuneiform was considered. Since the cuneiform is not aligned to the first metatarsal in parallel direction, the joint is inclined at an angle that differs from all other joints found in the feet. Conventionally four pins are used for stabilizing the fixator, two in the cuneiform and two in the metatarsal. The two dimensional model is built based on the dimensions of a prototype. The initial model is built, as a beginning phase that simplifies the structure. The problem is therefore defined as a plane stress 2D problem as the thickness is neglected. As in conventional practice four pins with 1mm in diameter are used. The width of rail is set to 5mm and the length to 15mm. For easy modeling the clamps in the external fixation device are not considered in the modeling.

3.2 Boundary conditions

The two farther ends of the bone are constrained in xy directions. The same constraint is applied to the joints where the pins are fixed on the rail. The other ends of the pins are not constrained. A uniform force of 0.5N is applied to the pins on the metatarsal side. As in the conventional practice no force is applied on the pins at
cuneiform side. A uniform gap of 1mm is maintained between the metatarsal and the cuneiform. The angle between the edges of the cuneiform and metatarsal are taken to be 2.043° as shown in Figure 3.1. The material for the pins and the rail is taken as stainless steel with Young’s modulus of 2.0e11N/cm², poisons ratio as 0.33 and density as 7950gm/cm³. The Young’s modulus for bone is taken as 73e8N/cm², poisons ratio as 0.3 and density as 2090gm/cm³. An initial mesh is developed with 5328 elements. The mesh is refined near the pins where the stress variations are more significant. Final mesh has 8267 elements. The problem is solved for displacements at the gap.

Figure 3.1- Boundary Conditions
3.3 Two Dimensional Analysis

Initially in 2D analysis factors effecting the bone fusion are studied. The parameters of fixation device defined in Figure 6 include distance at which the pin should be placed from the fusion site, width of the rail, length of the rail, diameter of the pin, separation distance between pins in one clamp, separation distance of rail from fusion site and angles of pin positioning are analyzed. The effect of positioning of pin at an angle is studied which is not employed in the surgery. For each of the parameter 8-10 cases were run. Once the principal factors that effect the fusion are determined analysis is performed to optimize the positioning of the fixation device with varying parameters.

![Two Dimensional Mesh with defined parameters](image)

Figure 3.2 – Two Dimensional Mesh with defined parameters
3.4 Three Dimensional Analysis

A similar analysis is done with the consideration of bone thickness. The factors that affect the gap are not taken into considered during 3D analysis. It is assumed that the same factors are going to effect as in the two dimensional case. The problem is solved to
find the optimal positioning of fixation device and hence it is solved for displacements for cases considering the variables that affect the fusion site in 2D analysis.

Figure 3.4-Three Dimensional Model

Figure 3.5-Three Dimensional Mesh with 14980 elements and 3472 nodes
Parameters used for characterizing the factors Effecting bone fusion and identifying the optimal positioning of the device for the external fixator are analyzed and discussed below. The gap portion is divided into three regions namely middle, left and right to identify the angular gaps that exist when the fixator is applied. The following Figure 4.1 shows these three regions of interest.

Figure 4.1-Fusion regions of interest
Figure 4.1 represents the complete fusion of the bones when the pins are placed at 33mm from the fusion site. We don’t observe any gaps near the fusion site. This figure illustrates complete fusion. Where as in Figure 4.3 we observe incomplete fusion. This is
the simulation when the pins were kept at 20mm from the fracture site. In this case, we see the metatarsal moving far away from its position and also it is not well aligned with the cuneiform. These types of fusions cause gaps at the fusion site making the joint unstable. These figures show the difference between the complete and incomplete fusions. In incomplete fusions we have different displacements at the three regions i.e middle, left and right areas where as in complete fusion all the displacements are equal. This criterion is taken as the key point in deciding whether the fusion is complete or not.

4.1 Effects of Positioning of pin

![Figure 4.4-Schematic Representation of changing position of pin](image)

Analysis is performed by varying the placement of second set of pins (on metatarsal side). This is shown by the arrow in the Figure 4.4. Initially the pins were kept at 10mm from fracture site and then gradually increased. This distance is increased until the gap is closed completely. At 33mm from fracture site, we found that the gap is closed.
completely. The cuneiform pins are kept 7mm from the fracture side as this is followed in the surgery. These pins are kept in a stable position and no force is applied on the cuneiform side. So in the analysis also these pins are stabilized in a fixed position. From Figure 14 we observe that as the distance from the fusion site is increased the displacement near the fusion site also decreases. This distance is increased gradually and we see that the gap is closed completely without any angles at the ends of the fusion site. The gap is closed at 33mm from the fusion site.

![Effect of Positioning of Pin](image)

**Figure 4.5 Effect of positioning of pin**
4.2 Effects of diameter of pin

The same analysis is carried out but with a different diameter of the pin at 2mm. Schematic representation of the diameter changes is shown in Figure 15. We observe from Figure 16 that the gap is closed uniformly at 33mm even for 2mm diameter pin. Further change in the diameter of the pin is not made, as the bones under consideration are very small. In this case we do see that the diameter is not a big factor to be considered in attaining stability from Figure 16. But this may be a prominent factor in large bones where there will be much scope to vary the diameter of the pin.
4.3 Effects of distance between metatarsal pin sets

Figure 4.7-Effect of pin diameter

Figure 4.8-Schematic representation of change in distance between pins
In conventional devices we observe that two pins on one clamp are maintained at the same distance at about 2-3mm. This distance cannot be changed and the whole clamp is moved to different place to change the position of one or both pins. So in this case we studied the effect of separation distance between the pins. Schematic representation of change in distance between pins is shown by Figure 4.8. The pins on cuneiform are maintained at 7mm from the fusion site. Analysis is done from 2mm separation distance until the gap is closed. The distance between the pins is changed on the metatarsal side. One of the pins on one clamp is fixed and the position of the other pin is changed. We found that at 20mm, the gap is approaching to close uniformly. This is shown in Figure 4.9
The distance between pins is further not increased, as this distance will not be feasible in the original device since the clamp cannot accommodate this distance.
4.4 Effects of distance of rail from fusion

![Schematic representation of change in rail distance](image)

Figure 4.10-Schematic representation of change in rail distance

There is always a debate over how far the rail should be kept from the fracture site. Generally the surgeon keeps the rail at 5mm from the fusion site. In the analysis, the rail is moved away from the fusion site gradually to see its Effect on the fusion. The rail distance is shown schematically in Figure 4.10. An analysis is carried out starting from 6mm to 14mm where the gap is closed uniformly. Here the pins are kept at 15mm from the fracture site. However, changing the position of the pin from fusion site will vary closing of the gap. From the graph in Figure 4.11 we observe that as the distance increases there are chances that the gap closes uniformly. Further distance is not increased as the gap is closed uniformly.
Effect of Rail distance from Fusion site

Figure 4.11-Effect of change in rail distance from fusion site

4.5 Effects of width of rail

Figure 4.12-Schematic representation of change in width of rail
This analysis is done to see whether there is any effect of the width of rail on closing gap. Figure 4.12 represents schematically the width of the rail. Usually the width of rail is about 5mm-8mm. The width of the rail is increased starting from 6mm to 22mm. As the width is increased, it is observed that the three displacements did not equal to each other resulting in an incomplete fusion. The distance is not increased further, as this is not a reasonable value. The result can be seen from Figure 4.13.

![Effect of width of Rail](image)

**Figure 4.13-Effect of width of rail**

In this case the pins on the cuneiform are kept at 7mm from the fusion site and at metatarsal side, they are kept at 17mm. From the above Figure 4.13 we see a sudden change in the displacement at 17 mm. This is not actually very high, but since we are looking in minute scale it appears large.
4.6 Effects of length of rail

Analysis is performed to see whether there is any effect of the length of rail on closing gap. The length of the rail in the conventional devices is around 15cm. The length of the rail is increased to 30cm. The change in the length of the rail did not aid in the complete fusion of the gap. This can be seen from the Figure 4.15 below which shows that the three displacements middle, right and left are not equal.
The distance is not further increased, as 30mm of the rail length is not a reasonable length.
4.7 Effects of third pin on stability

Figure 4.16-Schematic representation of third pin

Conventionally in the Lapidus Procedure, all the four pins are placed to achieve stability of the gap. This analysis is done to check whether all the pins are required or not. Since the force is applied on the fourth, we tried to see the effect of gap closing by removing the third pin at different positions. Figure 4.16 shows third pin. This analysis is same as the one with 3mm diameter pin except without the third pin. From the graph in Figure 4.17 we observe that third pin is required for stability. At a distance of 33mm where the gap is closed uniformly in the first case, we observe here that it is not achieved.
Figure 4.17-Effect of third pin on stability of the system
4.8 Effects of second pin on stability

In this case the second pin is removed as shown in Figure 4.18 on the cuneiform and same analysis is performed. From the graph in Figure 4.19 we see that the whole system is highly unstable without the second pin. Even though no force is applied on the first clamp directly, it is interesting to see this type of result. We can infer that the second pin acts as a supporting member.
4.9 Effects of fracture angle

This is an important parameter that influences the stability of the system. Initially the fracture angle is kept at $2.045^\circ$ for all the analysis. Gradually this angle is increased,
but the pin is kept parallel to the surface as usual. From the graph in Figure 4.21 we observe that the displacement is very high and unstable as the angle of fracture is changing. As the angle changes the gap will no longer be uniform but as the pins will be in parallel to the surface, we observe very high instability in the system. Hence the angle of fracture and the angle at which the pin is kept play an important role in the stability of the system as well as the gap closing.

Figure 4.21-Effect of fracture angle on fusion
4.10 Effect of pin angle

Figure 4.22-Schematic representation of negative angle of pin wrt x-axis

The analysis of angle parameter is more complicated. There are three parameters effecting the displacement when angle is varied, they are distance between the pins, positive or negative angle and distance from the fracture site. Positive angle is defined as the angle above the x-axis i.e towards the fusion site in this analysis and negative angle is considered as the angle below x-axis i.e away from the fusion site. After many simulations we found that there is an inverse relationship between the negative angle increase and the gap displacement, a direct relationship between the positive angle displacement and gap displacement. In order to close the gap completely by placing the fourth pin in the positive direction, the pin-to-pin distance in the second clamp should be 13mm and the pins are placed at 11mm from the fracture site.
At that point and at an angle of 4.08°, the gap is closed completely. But in practical case the gap between these pins will be around 2-4mm. So we changed the orientation of the angle in the negative direction so that the pin-to-pin distance can be reduced. In this way at 17 degrees of angle with respect to horizontal, and at a distance of 16mm from the fracture site the gap was closed completely with a 5mm pin-to-pin separation distance. From Figure 4.23 we see that the gap is closed at 17°.

4.11 Three Dimensional result

For 3D analysis FEMLAB 3.0 was used. As mentioned above 3D analysis was performed on positioning of pin parameter. The initial mesh was of 40248 elements. The problem could not be solved due to more mesh size. The mesh is then refined only at places where the stresses are high. The final mesh size was reduced to 14980 elements.
with 3472 nodes. The property values for bone and steel were taken as same in the two dimensional analysis. Only positioning of pin effect was simulated in this case.

As we observe the above graph, it is clear that it is similar to the result in 2D analysis. As the pin is placed away from the fracture site, the displacement is decreasing. But in this case, we observed that the gap closes when the pins were placed at 30mm from the fracture site. The complete and incomplete fusions can be seen from Figures 4.25 and 4.26 below. Blue color indicates low displacements and green color indicates high displacements.
4.12 Discussions

From the results we observe that there are certain parameters, which should be taken into consideration when the fixator is applied to the patient. In this case the pins at cuneiform are not subjected to loading, and hence the positioning of pins at cuneiform side is not effected. But placing two pins on the cuneiform offers stability to the system. This is clear from Figure 4.18 where the system is highly unstable without the second pin.
causing greater displacements. We also found that the gap can be closed effectively when
the pins are placed in an inclined position rather than in a straight manner. This can be
inferred from Figure 4.22. From the three dimensional analysis which is performed on
the positioning of the pin parameter we observed the result to be same as that we got in
two dimensional analysis. This can be observed from Figure 4.4 and Figure 4.23 that the
displacement decreases as the distance of pin from fusion site increase. Major factors
effecting the orientation of angle include pin-to-pin separation distance, distance from
fracture site and the direction of the angle. The effect of loading is not considered as a
variable in this analysis because the force that will be applied on the fixator will be
constant. But as a known fact as the external force is increased/decreased the loading on
the bone will be increased/decreased. As the stress is directly proportional to
displacement, stress plots are not included. The same mini fixator can be used with out
changing the design of it, if the pin is placed in a negative angle.
5.1 Conclusions

The human body contains different joints with different configuration. The results that are presented here are only for this type of bone joint and can be extended into other joint types with some modifications. The joint in consideration is small compared to joints such as tibia and femur. In those cases the parameters effecting the fusion found above can be a useful resource for other joint fusion scenarios. However the discussion for positioning distances and angles may vary significantly due to variation of bone. It also depends on the patient’s age and the configuration as well as orientation of the bone. This becomes important as the density is related to the fusion of the bones and age becomes a factor. The bone configuration is not same in all human beings. It varies with age also. But for most people all the orientation of bones will be similar. Table 1 shows the parameters effecting the fusion of the gap and Table 2 describes various alternatives to achieve complete fusion, in this case 1mm displacement.
Table 2-Parameters Effecting fusion

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Effect</th>
<th>Do not Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance of pin from fracture site</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Distance between pins</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Orientation of pins</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Distance of rail from fracture site</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Width of rail</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Length of rail</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Number of pins</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Diameter of pins</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>
Table 3 - Displacements at fusion site using various options

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Displacement near gap at distances from fracture site (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5mm</td>
</tr>
<tr>
<td>Distance of pin from Fracture site</td>
<td>3.65</td>
</tr>
<tr>
<td>Diameter of pin</td>
<td></td>
</tr>
<tr>
<td>2mm</td>
<td>3.81</td>
</tr>
<tr>
<td>3mm</td>
<td>3.65</td>
</tr>
<tr>
<td>Width of Rail</td>
<td></td>
</tr>
<tr>
<td>6mm</td>
<td>3.65</td>
</tr>
<tr>
<td>10mm</td>
<td>3.37</td>
</tr>
<tr>
<td>Length of Rail</td>
<td></td>
</tr>
<tr>
<td>15mm</td>
<td>3.65</td>
</tr>
<tr>
<td>20mm</td>
<td>3.65</td>
</tr>
<tr>
<td>Distance between pins</td>
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</tr>
<tr>
<td>3mm</td>
<td>3.65</td>
</tr>
<tr>
<td>15mm</td>
<td>1.93</td>
</tr>
<tr>
<td>Angle of fracture</td>
<td></td>
</tr>
<tr>
<td>2.000°</td>
<td>3.65</td>
</tr>
<tr>
<td>5.000°</td>
<td></td>
</tr>
<tr>
<td>Number of pins</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3.65</td>
</tr>
<tr>
<td>3</td>
<td>5.68</td>
</tr>
<tr>
<td>2</td>
<td>4.92</td>
</tr>
<tr>
<td>Angle of pin wrt negative y-axis</td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>3.65</td>
</tr>
<tr>
<td>17°</td>
<td>1.67</td>
</tr>
<tr>
<td>Distance of rail from fracture site</td>
<td></td>
</tr>
<tr>
<td>5mm</td>
<td>3.65</td>
</tr>
<tr>
<td>10mm</td>
<td>1.79</td>
</tr>
</tbody>
</table>
5.2 Recommendations

This thesis is a preliminary study of the effects of geometric parameters of the external fixation device on fusion. Only mechanical effects are taken into consideration when it comes to fusion of the joints. Since the area of the joint structures is considerable, fixator geometry will have greater impact on the final bone fusion result. In real scenario from Magnetic Resonance Imaging, the joint structure is very complicated with intricate contours. Currently we did not consider the MRI reconstructed images. The next topic will use the Magnetic Resonance images for geometric modeling for the optimum placement of the device. A full 3D analysis was not completed including all the parameters. We recommend taking into consideration the geometry and remaining parameters for further study. The software FEMLAB 2.3 used for analysis is not best suited for three-dimensional analysis while performing meshing. Using efficient software for both meshing and solving the structural problem are recommended. Bone density and its distribution in both the metatarsal and cuneiform, need to be included for simulating real world scenarios. Building bone correlation between various age and gender can be useful for better prediction of the optimal fixator location. The relationship for bone density change will be obtained through experimental techniques in next phase of research.
APPENDIX I

NOMENCLATURE

HV angle: Hallux Valgus angle
IMT angle: Inter Metatarsal angle
MTPJ: Metatarsophalangeal joint
DMAA: Distal Metatarsal Articulate Angle
APPENDIX II

FEMLAB Code

FEMLAB Model M-file
% Generated 24-Nov-2003 16:45:29 by FEMLAB 2.3.0.153.

flclear fem
% FEMLAB Version
clear vrsn;
vrsn.name='FEMLAB 2.3';
vrsn.major=0;
vrsn.build=153;
fem.version=vrsn;

% New geometry 1
fem.sdim={'x','y'};

% Geometry
clear s c p
p= [-0.25 -0.25 -0.20000000000000001 -0.20000000000000001; ... 
-0.10000000000000001 0.40000000000000002 -0.10000000000000001  ... 
0.40000000000000002];
r{= [1:4,[1 1 2 3; 2 3 4 4],zeros(3,0),zeros(4,0)];
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1; 1 0 1 0],zeros(2,0),zeros(2,0)};
CO1=solid2(p,rb,wt,lr);

p=[-0.2999999999999999 -0.2999999999999999 0 0; 0.25 0.299999999999999999 ... 
0.25 0.299999999999999999];
r{= [1:4,[1 1 2 3; 2 3 4 4],zeros(3,0),zeros(4,0)];
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1; 1 0 1 0],zeros(2,0),zeros(2,0)};
CO2=solid2(p,rb,wt,lr);

p=[-0.299999999999999999 -0.299999999999999999 0 0; 0.25 0.299999999999999999 ... 
0.25 0.299999999999999999];
r{= [1:4,[1 1 2 3; 2 3 4 4],zeros(3,0),zeros(4,0)];
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1; 1 0 1 0],zeros(2,0),zeros(2,0)};
CO3=solid2(p,rb,wt,lr);
objs={CO1,CO2,CO3};
names={‘CO1’,‘CO2’,‘CO3’};
s.objs=objs;
s.name=names;

objs={};
names={};
c.objs=objs;
c.name=names;

drawstruct=struct(‘s’,s,’c’,c,’p’,p);
fem.draw=drawstruct;
fem.geom=geomcsg(fem);

clear appl

% Application mode 1
appl{1}.mode=flpdeps(‘dim’,{‘u’,’v’,’u_t’,’v_t’},’sdim’,{‘x’,’y’},’submode’, ...
’std’,’tdiff’,’on’);
appl{1}.dim={‘u’,’v’,’u_t’,’v_t’};
appl{1}.form=’coefficient’;
appl{1}.border=’off’;
appl{1}.name=’ps’;
appl{1}.var={};
appl{1}.assign={’E’;’E’;’Fx’;’Fx’;’Fy’;’Fy’;’Kx’;’Kx’;’Ky’;’Ky’;’disp’; ...
’disp’;’e1’;’e2’;’e3’;’e3’;’ex’;’exy’;’exy’;’ey’;’ey’;’ez’; ...
’ez’;’mises’;’mises’;’nu’;’nu’;’rho’;’rho’;’s1’;’s1’;’s2’;’s2’;’s3’;’s3’; ...
’sx’;’sx’;’sxy’;’sxy’;’sy’;’sy’};
appl{1}.elemdefault=’Lag2’;
appl{1}.shape={’shlag(2,”u”)’,’shlag(2,”v”)’};
appl{1}.sshape=2;
appl{1}.equ.E=’2.06E11’;
appl{1}.equ.nu=’0.3’;
appl{1}.equ.Kx=’0’;
appl{1}.equ.Ky=’0’;
appl{1}.equ.rho=’7800’;
appl{1}.equ.gporder= {4;4};
appl{1}.equ.cporder= {2;2};
appl{1}.equ.shape= {1 2};
appl{1}.equ.init= { {0} ; {0} };
appl{1}.equ.usage={1};
appl{1}.equ.ind=ones(1,9);
appl{1}.bnd.Fx={'0'};
appl{1}.bnd.Rx={'0'};
appl{1}.bnd.Fy={'0'};
appl{1}.bnd.Ry={'0'};
appl{1}.bnd.type={'FxFy'};
appl{1}.bnd.gporder={0};
appl{1}.bnd.cporder={0};
appl{1}.bnd.shape={0};
appl{1}.bnd.ind=ones(1,28);
fem.appl=appl;

% Geometry
clear s c p
p=[0 0 6 6;0 150 0 150];
rh={l:4,[l 1 2 3;2 3 4 4],zeros(3,0),zeros(4,0)};
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1;1 0 1 0],zeros(2,0),zeros(2,0)};
CO1=solid2(p,rh,wt,lr);
p=[12 12 40 40;120 150 121 151];
rh={l:4,[l 1 2 3;2 3 4 4],zeros(3,0),zeros(4,0)};
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1;1 0 1 0],zeros(2,0),zeros(2,0)};
CO2=solid2(p,rh,wt,lr);
p=[12 24 28 40 40;119 78 0 68 0 120];
rh={l:3 5 6,[l 3 5 6],[1 3:5],[1 5;4 2;3 6],zeros(4,0)};
wt={zeros(1,0),ones(2,2),[l 1;0.70710678118654746 0.70710678118654746;1 1],...
zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1;1 0 1 0],zeros(2,0),zeros(2,0)};
CO3=solid2(p,rh,wt,lr);
p=[-2.9999999999999996 -2.9999999999999996 41 41;144 147 144 147];
rh={l:4,[l 1 2 3;2 3 4 4],zeros(3,0),zeros(4,0)};
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1;1 0 1 0],zeros(2,0),zeros(2,0)};
CO4=solid2(p,rh,wt,lr);
p=[-3 -3 41 41;127 130 127 130];
rh={l:4,[l 1 2 3;2 3 4 4],zeros(3,0),zeros(4,0)};
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1;1 0 1 0],zeros(2,0),zeros(2,0)};
CO5=solid2(p,rh,wt,lr);
p=[-3 -3 41 41;109 112 109 112];
rh={l:4,[l 1 2 3;2 3 4 4],zeros(3,0),zeros(4,0)};
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1;1 0 1 0],zeros(2,0),zeros(2,0)};
CO6=solid2(p,rb,wt,lr);
p=[-3 -3 41 41;92 95 92 95];
rb={[1:4,[1 1 2 3 2 4 4],zeros(3,0),zeros(4,0)];
wt={zeros(1,0),ones(2,4),zeros(3,0),zeros(4,0)};
lr={[NaN NaN NaN NaN],[0 1 0 1;1 0 1 0],zeros(2,0),zeros(2,0)};
CO7=solid2(p,rb,wt,lr);
objs={C01,C02,C03,C04,C05,C06,C07};
names={'C01','C02','C03','C04','C05','C06','C07'};
s.objs=objs;
s.name=names;
objs={};
names={};
c.objs=objs;
c.name=names;
objs={};
names={};
p.objs=objs;
p.name=names;
drawstruct=struct('s',s,'c',c,'p',p);
fem.draw=drawstruct;
fem.geom=geomcsg(fem);
clear appl

% Application mode 1
appl{1}.mode=fpdeps('dim', {'u','v','u_t','v_t'}, 'sdim', {'x','y'}, 'submode', ...
  'std','tdiff','on');
appl{1}.dim={'u','v','u_t','v_t'};
appl{1}.form='coefficient';
appl{1}.border='off';
appl{1}.name='ps';
appl{1}.var={};
appl{1}.assign={'E';'E';'Fx';'Fx';'Fy';'Fy';'Kx';'Kx';'Ky';'Ky';'disp'; ...
  'disp';'e1';'e1';'e2';'e2';'e3';'e3';'ex';'exy';'exy';'ey';'ey';'ez'; ...
  'ez';'mises';'mises';'nu';'nu';'rho';'rho';'s1';'s1';'s2';'s2';'s3';'s3'; ...
  'sx';'sx';'sxy';'sxy';'sy';'sy'};
appl{1}.elemdefault='Lag2';
appl{1}.shape={'shlag(2,"u")','shlag(2,"v")'};
appl{1}.shape=2;
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appl{1}.equ.Kx={'0'};
appl{1}.equ.Ky={'0'};
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appl{1}.equ.usage={1};
appl{1}.equ.ind=ones(1,31);
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appl{1}.bnd.Rx='0';
appl{1}.bnd.Fy='0';
appl{1}.bnd.Ry='0';
appl{1}.bnd.type='FxFy';
appl{1}.bnd.gporder={0;0};
appl{1}.bnd.cporder={0;0};
appl{1}.bnd.shape={0};
appl{1}.bnd.ind=ones(1,92);

fem.appl=appl;

% Initialize mesh
fem.mesh=meshinit(fem,...
    'Out', {'mesh'},...
    'jiggle', 'mean',...
    'Hcurve', 0.29999999999999999,...
    'Hgrad', 1.3,...
    'Hpt', {10,[]});

% Differentiation rules
fem.rules={};

% Problem form
fem.outform='coefficient';

% Differentiation simplification
fem.simplify='on';

% Material library
clear lib
lib.Mat2.name='ss';
lib.Mat2.E='2.1e11';
lib.Mat2.nu='0.33';
lib.Mat2.rho='7950';
lib.Mat2.type='material';
lib.Mat4.name='bone';
lib.Mat4.E='73e8';
lib.Mat4.nu='0.3';
lib.Mat4.rho='2090';
lib.Mat4.type='material';
fem.lib=lib;

% Boundary conditions
clear bnd
bnd.Fx={'0','0','0'};
bnd.Rx={'0','0','0'};
bnd.Fy={'0','867','0'};
bnd.Ry={'0','0','0'};
bnd.type={'FxFy','FxFy','RxRy'};
bnd.gporder={0;0},0;0,0;0};
bnd.cporder={0;0},0;0,0;0};
bnd.shape={0;0};
bnd.ind=[1 2 1 2 1 2 1 2 1 2 1 1 1 1 1 1 1 1 1 1 1]
2 1 1 1 1 1 1 1 1 1 1 1 1 3 3 3 3 1 1 1 1 1 1 1 1];
fem.appl{1}.bnd=bnd;

% PDE coefficients
clear equ
equ.E={'Mat2_E','Mat4_E','73e8','2.06E11','73e8'};
equ.nu={'Mat2_nu','Mat4_nu','0.3','0.3','0.3'};
equ.Kx={'0','0','0','0','0'};
equ.Ky={'0','0','0','0','0'};
equ.rho= {'Mat2_rho','Mat4_rho','1900','7800','1500'};
equ.gporder={4;4},4;4,4;4,4;4,4;4};
equ.cporder={2;2},2;2,2;2,2;2,2};
equ.shape={[1 2],[1 2],[1 2],[1 2],[1 2]};
equ.init= {{0;0},{0;0},{0;0},{0;0},{0;0}};{0;0}};{0;0}};{0;0}};{0;0}};{0;0}};{0;0}}
equ.usage={1,1,1,1,1};
equ.ind=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 1 2 1 2 1 3 4 5 1 1 1 1];
fem.appl{1}.equ=equ;

% Internal borders
fem.appl{1}.border='on';

% Shape functions
fem.appl{1}.shape= {'shlag(2,"u"),shlag(2,"v")'};

% Geometry element order
fem.appl{1}.sshape=2;

% Define constants
fem.const={};
% Multiphysics
fem=multiphysics(fem);

% Extend the mesh
fem.xmesh=meshextend(fem,'context','local','cplbndeq','on','cplbndsh','on');

% Evaluate initial condition
init=asseminit(fem,...
     'context','local',...
     'init', fem.xmesh.eleminit);

% Solve problem
fem.sol=femlin(fem,...
    'jacobian','equ',...
    'out', {'sol'},...
    'init', init, ...
    'context','local',...
    'sd', 'off',...
    'nullfun','flnullorth',....
    'blocksize',5000,....
    'solcomp', {'u','v'},...
    'linsolver','matlab',...
    'method', 'eliminate',...
    'uscale', 'auto');

% Save current fem structure for restart purposes
fem0=fem;

% Plot solution
postplot(fem,...
    'geomnum',1,...
    'context','local',....
    'tridata', {'mises','cont','internal'},....
    'trifacestyle','interp',....
    'tryedgestyle','none',....
    'trimap','jet',....
    'trimaxmin','off',....
    'tribar','on',....
    'geom', 'on',....
    'geomcol','bginv',....
    'refine', 3,...
    'contorder',2,...
    'phase', 0,...
    'title', 'Surface: von Mises stress (mises) ',....
    'renderer','zbuffer',...
'solnum', 1,...
'axisvisible','on')

% Differentiation rules
fem.rules={};

% Problem form
fem.outform='coefficient';

% Differentiation simplification
fem.simplify='on';

% Material library
clear lib
lib.Mat2.name='ss';
lib.Mat2.E='2.1e11';
lib.Mat2.nu='0.33';
lib.Mat2.rho='7950';
lib.Mat2.type='material';
lib.Mat4.name='bone';
lib.Mat4.E='73e8';
lib.Mat4.nu='0.3';
lib.Mat4.rho='2090';
lib.Mat4.type='material';
fem.lib=lib;

% Boundary conditions
clear bnd
bnd.Fx={'0','0','0'};
bnd.Rx={'0','0','0'};
bnd.Fy={'0','8670','0'};
bnd.Ry={'0','0','0'};
bnd.type={ 'Fx_Fy', 'Fx_Fy', 'Rx_Ry'};
bnd.gporder={ {0;0}, {0;0}, {0;0} };
bnd.cporder={ {0;0}, {0;0}, {0;0} };
bnd.shape={0,0,0};
bnd.ind=[1 2 1 1 2 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 1 1 ... 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 2 1 1 3 1 2 1 2 3 2 1 2 1 1 1 ... 1 1 1 1 1 1 3 3 3 3 1 1 1 1 1 1 1 1 1];
fem.appl{1}.bnd=bnd;

% PDE coefficients
clear equ
equ.E={'Mat2_E','Mat4_E','73e8','2.06E11','73e8'};
equ.nu={'Mat2_nu','Mat4_nu','0.3','0.3','0.3'};
equ.Kx={'0','0','0','0','0'};
equ.Ky={'0','0','0','0','0'};
equ.rho={'Mat2_rho','Mat4_rho','1900','7800','1500'};
equ.gporder={[4;4],[4;4],[4;4],[4;4],[4;4]};
equ.cporder={[2;2],[2;2],[2;2],[2;2],[2;2]};
equ.shape={[[1 2],[1 2],[1 2],[1 2],[1 2]]};
equ.init={{'0'},{'0'},{'0'},{'0'},{'0'},{'0'},{'0'},{'0'},... {'0'}};
equ.usage={1,1,1,1,1};
equ.ind=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 1 2 1 2 1 3 4 5 1 1 1 1];
fem.appl{1}.equ=equ;

% Internal borders
fem.appl{1}.border='on';

% Shape functions
fem.appl{1}.shape='shlag(2,"u")','shlag(2,"v")';

% Geometry element order
fem.appl{1}.sshape=2;

% Define constants
fem.const={};

% Multiphysics
fem=multiphysics(fem);

% Extend the mesh
fem.xmesh=meshextend(fem,'context','local','cplbnEq','on','cplbdsh','on');

% Evaluate initial condition
init=asseminit(fem,...
'context','local',...
'init', fem.xmesh.eleminit);

% Solve problem
fem.sol=femlin(fem,...
'jacobian','equ',...
'out', {'sol'},...
'init', init,...
'context','local',...
'sd', 'off',...
'nullfun','flnullorth',...
'blocksize',5000,...
'solcomp', {'u','v'},...
'lin solver','matlab',...
'method', 'eliminate',...
% Save current fem structure for restart purposes
fem0=fem;

% Plot solution
postplot(fem,...
  'geomnum',1,...
  'context','local',...
  'tridata',{'mises','cont','internal'},...
  'trifacestyle','interp',...
  'triedgestyle','none',...
  'trimap','jet',...
  'trimaxmin','off',...
  'tribar','on',...
  'geom',  'on',...
  'geomcol','bginv',...
  'refine', 3,...
  'contorder',2,...
  'phase', 0,...
  'title', 'Surface: von Mises stress (mises) ',...
  'renderer','zbuffer',...
  'solnum', 1,...
  'axisvisible','on')

% Differentiation rules
fem.rules={};

% Problem form
fem.outform='coefficient';

% Differentiation simplification
fem.simplify='on';

% Material library
clear lib
lib.Mat2.name='ss';
lib.Mat2.E='2.1e11';
lib.Mat2.nu='0.33';
lib.Mat2.rho='7950';
lib.Mat2.type='material';
lib.Mat4.name='bone';
lib.Mat4.E='73e8';
lib.Mat4.nu='0.3';
lib.Mat4.rho='2090';
lib.Mat4.type='material';
fem.lib=lib;

% Boundary conditions
clear bnd
bnd.Fx={'0','0','0'};
bnd.Rx={'0','0','0'};
bnd.Fy={'0','8670','0'};
bnd.Ry={'0','0','0'};
bnd.type= {'Fx,Fy','Fx,Fy','Rx,Ry'};
bnd.gporder={ {{0;0},{0;0},{0;0}}};
bnd.cporder={ {{0;0},{0;0},{0;0}}};
bnd.shape= {0,0,0};
bnd.ind=[1 2 1 1 1 1 2 1 1 1 1 2 1 1 1 2 1 1 1 2 1 1 1 1 2 1 1 1 2 1 1 1 3 2 1 2 3 2 1 2 1 1 1 ... 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];
fem.appl{1}.bnd=bnd;

% PDE coefficients
clear equ
equ.E= {'Mat2,E', 'Mat4,E', '73e8', '2.06E11', '73e8'};
equ.nu= {'Mat2,nu', 'Mat4,nu', '0.3', '0.3', '0.3'};
equ.Kx= {'0','0','0','0','0'};
equ.Ky= {'0','0','0','0','0'};
equ.rho= {'Mat2,rho', 'Mat4,rho', '1900', '7800', '1500'};
equ.gporder= {{4;4}, {4;4}, {4;4}, {4;4}, {4;4} }; 
equ.cporder= {{2;2}, {2;2}, {2;2}, {2;2}, {2;2} };
equ.shape= {[1 2],[1 2],[1 2],[1 2],[1 2]};
equ.init= {{{'0';{'0'}},{{'0'};'{0'}},{{'0'};'{0'}},{{'0'};'{0'}},{{'0'};{'0'}}, ... 
{{'0'}}};
equ.usage= {1,1,1,1,1};
equ.ind=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 1 2 1 2 1 3 4 5 1 1 1 1];
fem.appl{1}.equ=equ;

% Internal borders
fem.appl{1}.border='on';

% Shape functions
fem.appl{1}.shape= {'shlag(2,"u")', 'shlag(2,"v")'};

% Geometry element order
fem.appl{1}.sshape=2;

% Define constants
fem.const={};

% Multiphysics
fem=multiphysics(fem);

% Extend the mesh
fem.xmesh=meshextend(fem,'context','loeal','eplbndeq','on','cplbndsh','on');

% Evaluate initial condition
init=asseminit(fem,...
  'context','local',...
  'init', fem.xmesh.eleminit);

% Solve problem
fem.sol=femlin(fem,...
  'jacobian','equ',...
  'out', {'sol'},...
  'init', init,...
  'context','local',...
  'sd', 'off',...
  'nullfun','flnullorth',...
  'blocksize',5000,...
  'solcomp',{u',v'}},...
  'linsolver','matlab',...
  'method', 'eliminate',...
  'uscale', 'auto');

% Save current fem structure for restart purposes
fem0=fem;

% Plot solution
postplot(fem,...
  'geomnum',1,...
  'context','local',...
  'tridata', {'mises','cont','internal'},...
  'trifacestyle','interp',...
  'trieedgestyle','none',...
  'trimap', 'jet',...
  'trimaxmin','off',...
  'tribar', 'on',...
  'geom', 'on',...
  'geomcol','bginv',...
  'refine', 3,...
  'contorder',2,...
  'phase', 0,...
  'title', 'Surface: von Mises stress (mises) ',...
  'renderer','zbuffer',...
  'solnum', 1,...
  'axisvisible','on')
% Plot solution
postplot(fem,...
   'geomnum',1,...
   'context','local',...
   'tridata', {'disp','cont','internal'},...
   'trifacestyle','interp',...
   'triedgestyle','none',...
   'trimap', 'jet',...
   'trimaxmin','off',...
   'tribar', 'on',...
   'geom', 'on',...
   'geomcol','bginv',...
   'refine', 3,....
   'contorder',2,....
   'phase', 0,....
   'title', 'Surface: total displacement (disp) ',....
   'renderer','zbuffer',....
   'solnum', 1,...
   'axisvisible','on')
REFERENCES

[1] Normal And Abnormal Function Of The Foot, Merton L. Root, William P. Orein, John H. Weed


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Chairperson, Dr. Yitung Chen, Ph. D.
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Committee Member, Dr. Bingmei Fu, Ph. D.
Graduate Faculty Representative, Dr. Edward Neumann, Ph. D.