Review of Biomechanical Characteristics of Illizarov Ring Fixators Using FEA

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Abstract. Review of Biomechanical Characteristics of Illizarov Ring Fixators Using Finite Element Analysis (FEA) of implants and fixators were carried out. Various illizarov fixators used for fracture fixation and lengthening of bones were reviewed. The illizarov ring fixators were modeled and analyzed using ANSYS Workbench FEA software. The research gap was found after the review. In this review biomechanical characters of various researchers were studied, the various configurations of the illizarov fixators were studied. The mathematical model gives the use mathematics in analyzing the various fixators; it was reviewed in this paper. Invivo and invitro tests conducted by various researchers were carried out. It is concluded that the titanium implants are have youngs modulus equivalent to human bone and it has rigidity and strength which is very much required for the treatment of the bone fracture.

Keywords: Illizarov Ring, Finite Element Analysis, Fixators, Ansys, Titanium

1. Introduction

The illizarov fixators are applied on patients having injuries during accidents, shortening of the bone and nonunion of the bone. The surgeons fix the illizarov fixator on the patient’s leg, many configurations of the illizarov fixators can be made, and it depends on the injury on the patient. It is very difficult for the doctor to analyze the mechanical parameters of the illizarov fixator. The fixators may fail due this reason. The biomechanical characters should also be studied. To overcome all these difficulties Finite element analysis has to be carried. This helps the doctor to understand the illizarov fixator mechanical and biomechanical characters; before assembly on the patients leg for treatment. In this review paper the mechanical and biomechanical characters of the illizarov fixators will be discussed and the research gap is to be identified. Illizarov fixator is analyzed using FEA [1]. The Illizarov fixators are Modeled and Analyzed using the ANSYS Work Bench software package [2-4]. The load is applied on the fixator at the distal end near the knee joint. The following parameters of the illizarov systems were analyzed using the Finite Element Analysis [5-7]. The bone model is created using cadaveric human tibial bone, [8-9] The Poisson ratio and young's modulus of the fixator and bone nis given the table 1.

The objective of this review paper is to find the research gaps in the construction of the illizarov fixators. This will help to reduce the healing time of the bone and quick recovery of the patients.
Table 1. Material Properties of metals used in FEA

| Material   | Young"s modulus | Poisson Ratio |
|------------|-----------------|---------------|
| Titanium   | 110             | 0.31          |
| SS         | 210             | 0.3           |
| Magnesium  | 45              | 0.35          |
| Aluminium  | 70              | 0.33          |

2. Biomechanical Characteristics of illizarov Fixators

Many researchers have carried out study on Fixators, in particular Illizarov fixators. These experimental studies are time consuming it takes longer time to complete the test. FEA is a method to analyze biomechanical problems.

2.1 Illizarov fixators and Mechanical Properties

The different Configurations of Monticelli–Spinelli and Illizarov external fixator and tested to define the mechanical properties. They studied five configurations with the external fixator consists of rings with tensioned wires (circular) [10-11]. While in one configuration pairs of the tensioned wires and their corresponding ring were replaced by threaded bars (hybrid). Testing is performed in an axial compression, bending and torsion. This result is compared to the characteristics of a linear fixator groups. Both the circular and the hybrid configurations stiffness graphs were non-linear in compression. In bending, circular fixator is also having a similar pattern in both anterio posterior and oblique loading directions. The bending loading displacement pattern for the hybrid fixator was similar to that of the linear fixator. In torsion test stiffness graph is linear for both circular and hybrid fixator. Hybrid configurations observed by the researcher in terms of mechanical behavior, having characteristics from both linear and circular fixators. The researcher observed that the above configuration showed different types of stiffness curves. So they are not similar fixator. Thus from the above groups it can be concluded that the three above groups own different mechanical performance and also it can be considered as different types of fixators. Very few researchers analyzed the load at the fracture site invivo and invitro. Since there are many typpe of fixators to be analyzed. Finite Element Analysis can be carried out. It is hoped that this paper goes some way to meeting this need.

The work analyzed the distribution of stress and reasons for fracture at various regions on the component one has to know clearly about the various types of loads and also the moments that are acting on the component [12]. So in order to have a clear idea about the loads, it is inferred from their research that the immediate effect of mechanical stress on organic tissue, pressure is the specific stimulus for the bone formation, tension for the differentiation of fibrous tissue and the shear for the formation of cartilage. Illizarov method of treating bone fracture is also termed as tension stresses for the bone growth due to mechanical forces. The work on the fixators, fabricated fixator plates using composite materials. Researcher observed composite plates have tendency to delaminate in solution [13].

The Finite Element Analysis of Fixators to analyze the problems in design were studied [14]. The researcher observed that much research has not been conducted on the distribution of stress on the neck of the femur and the fixator using Finite Element Analysis. It is hoped that this thesis goes some way to meeting this need. It investigated on linear elastic deformations for plane curved beams in the plane loaded using the finite element method and they made a comparison between the calculus methods of linear elastic deformations for plane curved beams in their plan loaded. They concluded that the classic calculus was limited by the simplifying hypothesis, whereas FEM can be solved by mathematical model [15].

2.2 Different configuration of illizarov fixator

The test has different Configurations of Monticelli–Spinelli and Illizarov external fixator to define the mechanical properties. In five configurations, the external fixator consists of rings
with tensioned wires (circular), while in one configuration pairs of the tensioned wires and their corresponding ring are replaced by threaded bars (hybrid) [16]. Testing is performed in axial compression, bending and torsion. The results are compared to the characteristics of a linear fixator groups. Both the circular and the hybrid configurations are non-linear in compression. In bending circular fixator has a similar pattern in both anterioposterior and oblique loading directions. The bending loading displacement pattern for the hybrid fixators is similar to the linear fixator and higher inplane stiffness of pins. In their work studied about the strength of different fixation techniques for bicondylar fractures, a biomechanical study used synthetic material (saw bones tibia) has mechanical properties similar to the human cancellous bone and consistent material property and geometry. Acrylic can also be used as bone in the case of tibia bone [17]. In their work pointed out that on three dimensional load measurements in an external fixator using hexapods. The hexapods offers the advantage that fixator load can be measured in all six special degrees of freedom which are 3 forces and 3 movements measured with the hexapod all determination of shear forces in the fixator, values of the order of magnitude of the axial load [18].

Torsion was linear for both circular and hybrid fixator, as for the linear fixators by combinations of wires and pins (hybrid configurations) in mechanical behaviour had characteristics from linear and circular fixators.

2.3 Mathematical model and illizarov fixator

The research investigated on linear elastic deformations for plane curved beams in the plane loaded using the finite element method and they made a comparison between the calculus methods of linear elastic deformations for plane curved beams in their plan loaded. They concluded that the classic calculus was limited by the simplifying hypothesis, whereas FEM can be solved by mathematical model [19]. In their work addressed the problems using mathematical formulation for a pretensioned slender beam [20]. Analytically modelled kirschner wires in Illizarov circular external fixator as pretensioned slender beams in their work, mathematically formulated a pretensioned slender beam tension due to lateral loading, by Central loading of a pretensioned slender beam was studied and a new polynomial equations and derived, the roots for various loading conditions on the fixator. Finite Element Analysis for k-wires of illizarov ring fixators are checked and validated by 2D,and 3D.

2.4 Invivo Experimental work

The studied on low intensity stimulation in distraction osteogenesis in rabbits and the low intensity pulsed ultrasound have shown to accelerate fracture healing [21]. The research studied the complications of ring fixators in the foot and Ankle reviewed by 12 years’ experience of the foot and ankle replacement. The majority of the complications are due to post-operative complications [22]. Number of joint stiffness, wire breakage, axial deviation is some of the complications. Exercise is the most important measures in avoiding the majority of complications arising from joint stiffness. Wire breakage occurs when heavy load falls on the fixator. The research focused on the effects of external fixation and limb lengthening on peripheral nerve function to identify the factors affecting peripheral nerve function during limb lengthening on goats [23]. Although there was a correlation between the amount of lengthening performed and the degree of evoked potential deterioration the anatomic relationship between the wires and nerves is more important factor in the development of these abnormalities. He recommended that external fixation techniques can be refined to minimize soft tissue fibrosis and encroachment of peripheral nerves by transfixing wires or half pins demonstrated the shorter fracture healing times in tibia fracture [24-26].

2.5 Effect of fatigue on Illizarov fixator

Examined the fatigue effect of elastic interfragmentary motion on unilateral Fixators, by loading pneumatic drivers to apply nominal axial (220N) at frequency of 1Hz. Studies can be carried out on illizarov fixators to examine fatigue [27].
2.6 Complications in Ilizarov fixator

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2.7 Effect of Bone Screws on Ilizarov fixator

The work designed and tested external fixator bone screws. They studied the external fixation bone screws loosening. In addition, he studied the design factors influencing the bone screw interface experimentally for various screws, with the intention of minimizing the strength and stiffness of the inserted screws. Push in, Pull out and bending tests are carried out on the experimental screws and on two commercially available across in both a synthetic material and in cadaveric bone. The results of the push-in and pull out tests indicate that both the screws thread form and cutting head have significant effect in the holding strength of the screws. The results of the push-in and pull-out test can be used in the assembly of illizarov hybrid fixator [30].

2.8 Stiffness and stability of illizarov fixator

It showed that there is not a direct correlation between the stiffness and stability. The lowest axial stiffness without deformation plastically is demonstrated by the Illizarov fixator. For maximum stability and minimum shear, the wires should be placed as close to $90^\circ/90^\circ$ situation as the anatomy safely permits [31]. The experimentally studied the multivariable biomechanical analysis of stability of external circular fixation and the stability of bonefragments within circular external fixator is affected by the manipulation of the parameters of fixation or individual components of the frame. The contribution of each component of the frame to overall bone fragments stability is dependent upon the mode of loading, ring diameter, determining, the length of the wires has the greatest effect on stability of fixation as shown figure1. Finite element analysis can be compared with the experimental results [32].

![Figure 1](image)

Figure 1 The Illizarov configurations that were tested

The experiment analysed the external fixators for femoral bone is elongated. The aim of the laboratory investigation is to determine the displacement of the bone fragments as a function of the external load and construction of the fixator. The clinical study revealed the loading acting on the particular supported rods of the fixator and it changes during elongation of the lower limb in the thigh section. They demonstrated that the stability the of the illizarov fixator system [33]. The work showed that if four rings are used to fix a (artificial) simulated fracture in the tibia bone, the stability of the fixator configuration increases when the two middle rings are fixed closer to the fracture site and other two rings are fixed to the proximal and distal end of the bone [34].
2.9 Illizarov fixator and K-Wire

The research showed that the counter opposed olive wires reduces slippage of the wires in the bone, and increases the stability of fixation for oblique fractures. This is one of the advantages for deformity correction or deformity prevention, during limb lengthening [35].

The number of wires used and number of levels of fixation were important. As the number increases, so the stability of numbers levels of fixation were important. This can also be proved by finite element analysis [36].

A load for certain cases the shear movement at the fracture site is substantial up to 4mm and in all cases it is as significant as axial displacement. During average full weight bearing all the fixator bone screws frameworks will allow too much axial movement at the fracture. This could inhibit healing and cause peak bone and screw stresses to approach yield. The main cause of frame work flexibility was pin bending and this can be reduced by fitting the fixator close to the limb.

2.10 Fatigue and Illizarov fixator

The work highlighted Rapid application fracture fixation an evaluation of mechanical performance, evaluated pinless and centrafix fixation for rapid application of tibial fracture in disaster and battle field, fixator fatigue strength. At last none of the above fixator showed any successive change in the amplitude of dynamic displacement arising from fatigue, all fixators suffered to some loosened clamping screws as a result of 10,000 cycles [37]. The experiments can be conducted for more number of cyclic. The cyclic axial bending of bone is important for maintaining bone mass and remodeling [38]. The work could not show such effect for cyclic lateral bending loads in their work [39].

The monitored techniques of bone fracture healing using external fixators. The treatment of long bone fractures by external fixators offers a unique opportunity to control healing of the fracture by measuring the compression of the frame, that occurs under the load given to the bone and rely on the mechanical properties of the fracture. Invitro, the external fixators assembled on the bone is tested on universal testing machine to measure the compression of the frame [40].

2.11 Stiffness of Illizarov fixator

The relative stiffness, transverse displacement and dynamization are comparable external fixator. unilateral fixator was tested as given in the table:1 under applied axial, bending and torsion addition to this bone and screw stresses reach levels that are close to yield for average weight bearing and may lead to failure in cases of more flexible frame configuration or higher loading. When load on the fixator is high hybrid fixators may be used [41].

| Maximum load(N) Before/After Unlocking | Maximum Axial Displacement (mm) Before/After Unlocking | Maximum Transverse Displacement (mm) Before/After Unlocking |
|----------------------------------------|--------------------------------------------------------|-----------------------------------------------------------|
| 621/567                                | 0.95/0.58                                              | -0.47/-0.51                                               |
| 143/184                                | 0.47/0.68                                              | +0.18/+0.20                                               |
| 565/488                                | 0.15/0.25                                              | -0.15/-0.31                                               |
| 192/147                                | 0.55/0.46                                              | -0.24/-0.27                                               |
| 379/438                                | 0.09/0.13                                              | -0.11/-0.16                                               |
| 295/147                                | 0.67/0.57                                              | +0.43/+0.41                                               |
| 699/667                                | 0.29/0.28                                              | -0.34/-0.37                                               |
| 283/379                                | 0.22/0.21                                              | +0.65/+2.19                                               |
| 111/180                                | 0.61/0.51                                              | +0.17/+0.47                                               |
| 484/376                                | 0.57/0.49                                              | -0.21/-0.25                                               |
The work pointed out that parameters affecting axial stiffness of tibial fixation in an illizarov angle distractor. For end stage osteoarthritis patients, ankle distraction permits partial regeneration of the articular surface. Therefore a configuration specific finite element model of an illizarov ankle fixator was developed to identify frame configuration adequate for that purpose. Increasing the half-pin diameter from 6mm to 7mm resulted in a 21% decrease in displacement while reducing the diameter to 4mm displacement by 84% is increased. FE model was used for intraoperatively for patient specific determination of fixation rigidity [42].

3. Review of Methodology
The methodology adopted by various researchers is reviewed in this section. Applied Ilizarov principle used a monolateral fixator that allows axial dynamization. While Ilizarov started distraction in 5 to 7 days started at 14 days to allow for increased callus formation. This has been termed 'CALLOTASIS' was reported by the researcher this method is simple, safe and well tolerated by children and adolescents with moderate limb length discrepancy. But using this method for large defects and for adults was not supported by these authors. The problems faced by the researchers divided the difficulties during limb lengthening as problems, obstacles and complications. He considered all intraoperative injuries, problems that were not solved before the end of treatment were considered true complications. The complications included, muscle contractures, joint luxations, axial deviation, neurologic injuries, vascular injury, premature consolidation, delayed consolidation, non-union, pin-site problems and hardware failure. Late complications included, loss of length, late bowing, refracture and joint stiffness. Pain and difficult sleep were other in prolonged cases. An examination model is prepared using bone equivalent material. It is meshed using tetrahedral component of dimension of 500μm is used 49170 numbers of basics and 592088 numbers of nodes. Loading was carried out with three times the body weight. The above analyzes is carried out using ANSYS Workbench Software Package.

3.1 FEA Fixator Samples
Illizarov fixator, cadaveric tibia model, Poisson ratio of the fixator is 210GPa and 0.3 and for bone is 20 GPa, 0.27.

3.2 FEA Fixator Tools
ANSYS Package Software for modeling and Analysis. The tools used for analysis of the Illizarov fixator consists of threaded rods, fixed on the Illizarov rings, k-wires transfix the bone and the k-wires are fixed on the ring. The rings are placed on the proximal and distal end of the bone. A fracture gap of 3mm is artificially created by the surgeon.

4. Review of Experimental work of various researchers
Applied Ilizarov principle used a monolateral fixator that allows axial dynamization. While Ilizarov started distraction in 5 to 7 days, other researchers started at 14 days to allow for increased callus formation. This has been termed 'CALLOTASIS'. This method is simple, safe and well tolerated by children adolescents with moderate limb length discrepancy. But using this method for large defects and for adults was not supported by these authors. The difficulties during the limb lengthening have problems, obstacles and complications. He considered all intraoperative injuries; problems that were not solved before the end of treatment were considered true complications. The complications included, muscle contractures, joint luxations, axial deviation, neurologic injuries, vascular injury, premature consolidation, delayed consolidation, non-union, pin-site problems and hardware failure. Late complications included loss of length, late bowing, refracture and joint stiffness. Pain and difficult sleep were other in prolonged cases.

4.1 Coordinate system and loading
The coordinate system X-Y-Z of this tibial Implant is based on the following definitions. The centre of the knee is chosen as the origin and the plane of the paper is chosen as the X-Y Plane with x-axis in the horizontal direction as well as y-axis in the vertical direction as well as the
direction perpendicular to the plane of the paper is taken as Z Axis.

4.2 Implant Dimensions
The fixator dimensions are based on the patients fracture type. All types of rings like half ring, semi half ring and full rings are available.

4.3 Meshing
Meshing the model is the first step for FE analysis after the model has been generated. In order to analyze the model, it should be meshed with suitable element and element is the key factor. The model is meshed using solid 72 tetrahedral element which is four node component with six degrees of autonomy. The model that has been produced as well as meshed into 26,202 basics having 5430 nodes using solid 72 tetrahedral fundamentals.

4.4 Assumptions and restrictions
The following assumptions are made
- Solid 72 uses mixed method with steady cut off strains.
- The component should have zero volume.
- Where appropriate “h” method of convergence has been chosen for the analysis.
- The material is assumed as isotropic.
- Static loading has been done and Influence of fatigue loading is taken into consideration.
- Boundary conditions were applied on the model for analysis.
- Applied force loads on a component face are mechanically changed to the corresponding force

5. Results Obtained by various researchers
The FEA results of various researchers are summarized below for the illizarov configurations. Figure 2 shows the deformation of fixator and steel K-Wire, Figure 5 shows the fixator mesh view.

5.1 Illizarov Fixators various Parameters

![Figure 2 Total deformation, Titanium fixator and steel K-Wire](image)
Table 3  Illizarov Fixator various Mechanical parameters

| Parameters of the illizarov fixator | Aluminum fixator | 316L Stainless Steel fixator | Titanium fixator |
|------------------------------------|------------------|-----------------------------|-----------------|
| 1. Directional Deformation         | 0.00079802       | 0.00067593                  | 0.00076193      |
| 2. Elastic Strain Intensity        | 0.43402          | 0.3623                      | 0.38405         |
| 3. Equivalent Elastic Strain       | 0.27902          | 0.233                       | 0.24153         |
| 4. Equivalent Stress               | 1.43E+10         | 1.23E+10                    | 1.37E+10        |
| 5. Minimum Principle Elastic Strain| 3.07E-05         | 1.50E-05                    | 2.22E-05        |
| 6. Maximum Principle Stress        | 1.35E+10         | 1.14E+10                    | 1.29E+10        |
| 7. Maximum Principle Elastic Strain| 0.25002          | 0.2209                      | 0.2505          |
| 8. Maximum Shear Elastic Strain    | 0.43402          | 0.3623                      | 0.38405         |
| 9. Maximum shear stress            | 7.18E+09         | 6.20E+09                    | 6.93E+09        |
| 10. Total Deformation              | 0.06482          | 0.058122                    | 0.066528        |

Figure 3 shows the Illizarov was modeled by ANSYS Workbench Software. The load was applied on proximal end near the knee joint. Figure 4 shows the three types of fixator Ring materials were used in the finite element analysis are Aluminium, Titanium, and 316LSS.

Figure 3 Illizarov fixator with rachose cube

Figure 4 Illizarov fixator 300/300 K-Wire
Figure 5 K-Wire Illizarov ring fixator mesh

Table 4 Material Properties of stainless and the four pre-tension cases

| Material Properties | Initial extension in mm | Pre-tension (N) |
|---------------------|-------------------------|-----------------|
| E₁=193 GPa, E₂=96.5GPa, σ₁=520MPa, σ₂=1300MPa, Transverse bending, P_{min}=0N, P_{max}=250N | | |
| Case-1              | 0                       | 0               |
| Case-2              | 0.1222                  | 4               |
| Case-3              | 0.2443                  | 8               |
| Case-4              | 0.3665                  | 1               |

5.2 Carbon Epoxy Composite Illizarov ring

Carbon Epoxy specimen is prepared as per the standard procedure and test. The figure 6 shows Carbon Epoxy Composite Illizarov Ring used in the Illizarov fixator. The ring is cut with the help of water jet machining.
The work on the fixators, fabricated fixator plates using composite materials. Researchers observed composite plates have tendency to delaminate in solution. Many researchers have carried out study on Fixators, in particular Illizarov fixators. These experimental studies are time consuming it takes longer time to complete the test. FEA is a method to analyze biomechanical problems. It is hoped that this thesis goes some way in meeting this need.

6. Conclusion

The various implants and fixators were designed and analyzed for various types of bone fractures by the researchers. They found that the illizarov fixator with rachose cube is stiffer than other types of fixator and can take on more load. The illizarov fixator with 30°/30° K-Wire angles is dynamically best design for bone lengthening.

The various parameters which were analyzed using ANSYS work bench it was found the fixator with titanium/316 LSS k-wire is the better fixator than Aluminium/316 LSS K-wire, Stainless Steel/316 LSS K-wire.

From the literature review it is also concluded that the three studied groups own different mechanical performance and can be considered as different types of fixators. The mechanical characteristics of an external fixator determine the biomechanical environment of a fracture, osteotomy or non-union treated by the fixator. Two main categories of fixator are in regular use. The more conventional type (e.g., Hoffmann) relies on larger diameter (4mm to 6mm) stiff pins for its stability. Upon loading, these pins act as cantilevers and generally threaded so as to fix to the bone.

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