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Computer-Aided Design and Analysis of an Advanced Fixator System

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Abstract

The use of fixators is crucial during the healing process of fractured bones to ensure proper alignment and protect the bone against new mechanical stresses. Fixators are commonly utilized in procedures such as bone lengthening (distraction osteogenesis) and the correction of bone deformities. Distraction osteogenesis is a surgical technique that enables bone elongation and reshaping. In this study, an alternative fixator design is proposed to stabilize bone fragments during the distraction osteogenesis procedure applied to the femur bone. The fixator designs were created using SolidWorks 2021 software, and static analyses of the femur and fixator were conducted in ANSYS 2023 R1, considering geometric shapes and material properties. The analysis results were used to evaluate the integration efficiency of the fixator with the femur, its load-bearing capacity, and potential structural weaknesses.

Keywords: *Biomechanics, Static analysis, Fixator, Lengthening*

1. Introduction

The system that forms the shape of the human body and enables its movement is referred to as the locomotor system. The locomotor system consists of the skeleton, muscles, and joints. Bones are a crucial component of the skeletal system, serving to support the body, protect it from external impacts, and facilitate movement [1,2]. The femur bone is the longest, strongest, and heaviest bone in the human body, comprising a single segment. The length of the femur constitutes approximately 26% of an individual's height, with an average mass of 0.455 kg [3]. In a standing position, the femur is oriented from top to bottom and positioned obliquely from lateral to medial. The femur possesses a distinctive geometric structure, characterized by a slight anterior curvature and a distal end located posterior to the proximal end. The convexity of this curvature faces forward. The femur consists of a shaft and two ends, proximal and distal. The shaft is relatively smooth in structure, whereas irregularities are observed at its ends. It is long, slender, and nearly cylindrical in shape. The distal end is larger than the proximal end [4]. The femur can be divided into three main regions: proximal, shaft, and distal. The distal end is larger than the proximal end. The proximal region is particularly significant as it plays a vital role in transmitting weight from the upper body to the legs and joints. The proximal region includes the head, neck, and trochanter areas [5]. Distraction osteogenesis is a surgical technique used for shaping and lengthening long bones, such as the femur. This method has emerged as an alternative to conventional bone grafting techniques by enabling the rapid formation of viable bone through mechanical stimulation of the bone structure [6-8]. It allows osteotomies to be performed without disrupting the periosteum and vascular structures of the bone, facilitating the gradual separation of bone segments [9]. One of the most important tools used during distraction osteogenesis to ensure the stable separation and healing of bone segments is the fixator. Fixators are systems that provide external support to fractured bones by securing pins or wires inserted into the bone [10,11]. These fixators, widely used for various orthopedic conditions and injuries, consist of Kirschner wires, parallel rings, and threaded rods [12,13].

This treatment, particularly applied to large bones such as the femur, begins with the surgical division of the bone into two parts, which are then stabilized using fixators. The separated bone segments are gradually moved apart with the help of the fixator. To enable the gradual lengthening process, the pins in the fixator are adjusted four times a day, each turn extending the

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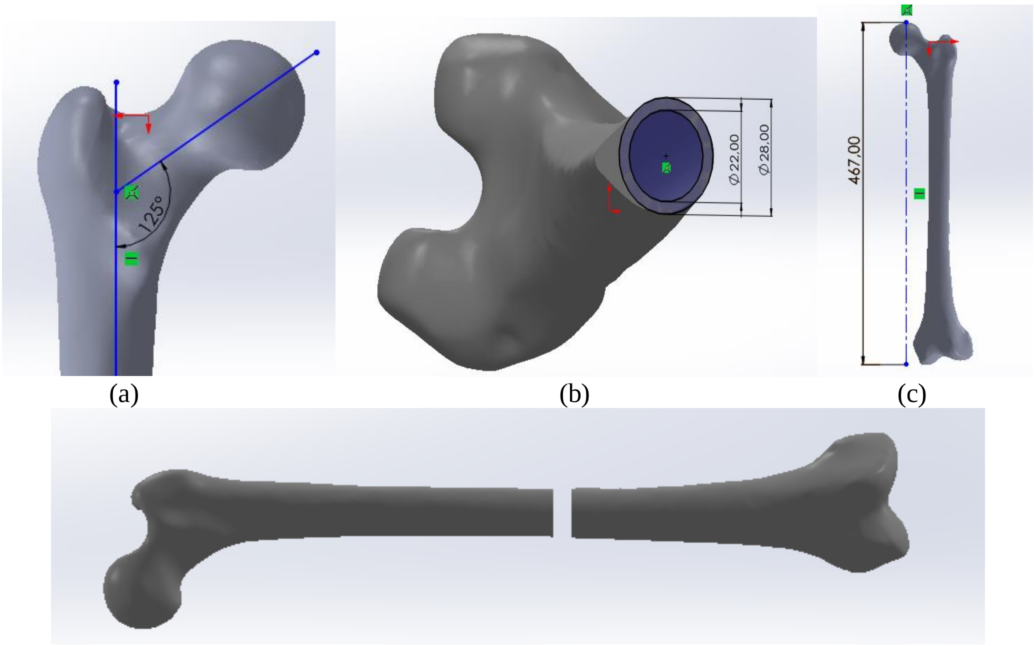
bone by 0.25 mm, resulting in a daily lengthening of 1 mm. This controlled distraction stimulates the continuous formation of new bone tissue. As the gap between the bone ends increases, the body continues to produce bone tissue until the desired length is achieved. Over time, the bone solidifies and heals. At this stage, the patient can gradually bear more weight on the affected limb. The overall success rate of the procedure is approximately 95% [14,15].

In this study, an advanced fixator design and its analyses are presented as an alternative to manual external fixators to ensure the stability of bone fragments during the distraction osteogenesis procedure applied to the femur. Static analyses were conducted on the femur and the fixator, and based on the results of these analyses, the efficiency of the fixator's integration with the femur, its load-bearing capacity, and structural weaknesses were evaluated.

2. Methods

This study was conducted using a unilateral external fixator. There are numerous unilateral fixators available on the market. Based on the research findings, the LRS type (Limb Reconstruction System, Orthofix, Italy) was selected due to its significantly better stability compared to other unilateral fixators. The dimensions of the designed LRS type fixator were obtained from the Orthofix Orthopedics catalog [16]. The femur model used in this study was uploaded by Samanwita Bagg on August 7, 2023, to the website https://grabcad.com/library/femur-bone-10, and this bone was used in the analyses [17]. The neck-diaphysis angle of the examined femur was determined to be 125°, with no signs of coxa vara or coxa valga deformities observed. The average length of the bone was found to be 467 mm, with a large diameter of 28 mm and a small diameter of 22 mm at the shaft. In the femur model used in this thesis, a fracture line has been created as done in distraction osteogenesis. This fracture line is 10 mm in length. The femur bone used and the fracture line created are shown in Figure 1.



(a) (b) (c)

(d)

Figure 1. Femur bone a) Neck diaphysis angle, b) average body diameter, c) height d) 10mm fracture line.

With these values, the critical load applied to the bone and the buckling stress that will occur in the cross-section have been theoretically calculated.

Fkr = Critical Load (N)
E = Elastic Modulus (N/mm^2)
I= Minimum Moment of Inertia of Column (mm^4)
Lk= Buckling Length (mm)
σ_{kr} = Buckling Stress (N/mm^2)
A = Cross Section Area of Column (mm^2)
d_1 = Outer Diameter
d_2 = Inner Diameter

The formula to be used for the calculation of the critical load is as follows:

$$F_{kr} = \pi^2 EI/L_k^2 \quad (1)$$

The calculation of the modulus of elasticity and the moment of inertia for the femur bone is as follows:

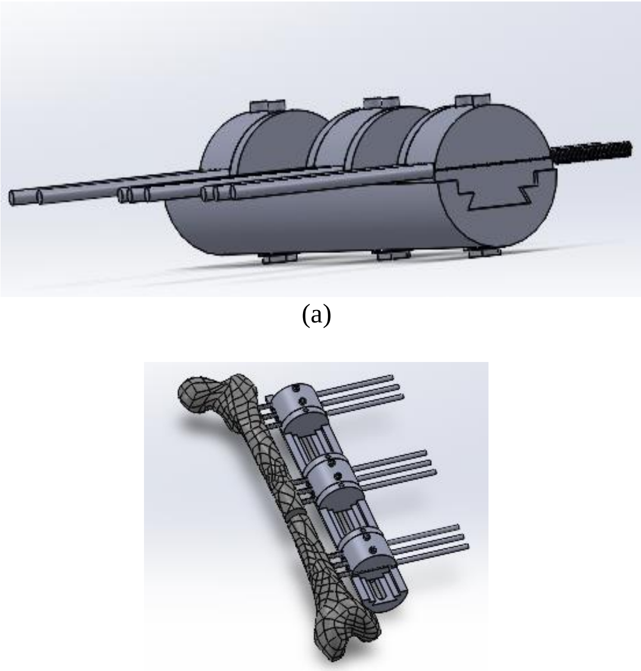
$$E = 17.10^{9}\ Pa = 17.10^{3}\ MPa$$

$$I = \pi.({d_1}^{4} - {d_2}^{4})/64 = 18663{,}375\ mm^{4} \quad (2)$$

Critical load result:

$$F_{kr} = 3585{,}95\ N \quad (3)$$

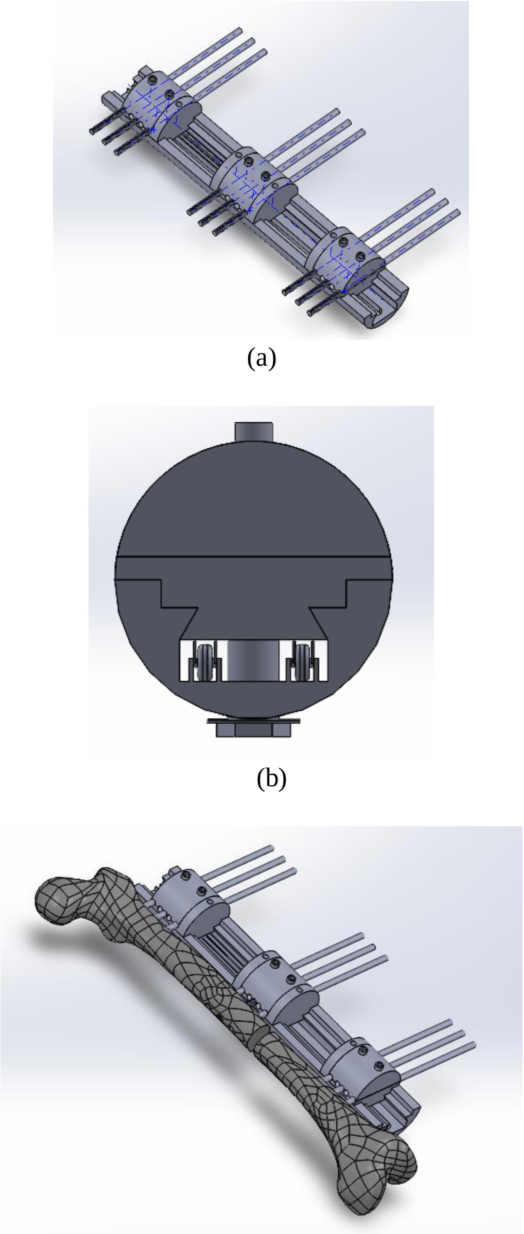
The limb reconstruction system is a unidirectional rail system consisting of interconnected Shanz pins, rail rods, and sliding clamps. By adjusting the rail system, limb lengthening or straightening can be achieved, joint deformities can be corrected, and missing, infected, or abnormally formed bone can be replaced. Designed to provide rigid fixation of fractured segments, it allows early weight-bearing and reduces economic burden, making it specifically tailored for the surgeon to perform simple and effective surgery [16].


(a)

(b)

Fıgure 2. a) LRS system b) LRS System assembled with femur bone.

The fixator rail is a robust structure, consisting of a small platform with linear bearings that include sliding components. A precise screw assembly mechanism is used to ensure the controlled positioning of the clamp parts along the rail axis. The guide screw used in the system is equipped with various tips and shaft configurations, compatible with almost any type of rotary power source. The rail varies in length according to the bone length and comes in several different sizes, including 120 mm, 200 mm, 250 mm, 300 mm, and 350 mm. These sizes are further classified into extra-short, short, standard, long, and extra-long categories [16]. The clamps slide along the axis of the rail in a controlled manner, and the clamp screws secure the clamps to the rail system. The dimensions of the clamps vary according to the length of the rail. The LRS system is shown in Figure 2.


(a)

(b)

(c)

Figure 3. The designed fixator a) 3D design, b) view of the design from different angle c) with the femur bone

As seen in LRS fixators, the design incorporates dovetail bearing systems. Modifications were made in the system's design to reduce the coefficient of friction for the motor-driven operation. In the improved fixator design, a different approach was considered to reduce the power consumption of the motor and ensure that the clamps can easily slide along the rail.

Based on the information obtained from the literature, it was found that the coefficient of friction in rolling elements is lower than that of sliding friction [18]. Therefore, in the new fixator design, a dovetail bearing model was developed and placed beneath the dual rolling-element clamps. This reduction in friction aims to decrease the power required by the motor. Based on the information obtained from the literature review, a load of 750 N was applied to the femur. Consequently, the motor selected should be sensitive to forces within the range of 750–1000 N.

The components used in the designed fixator system include the fixator rail, clamps (central, straight), clamp screws, rolling elements, and screws used for bone fixation. The designed system is shown in Figure 3. A motion mechanism has been incorporated beneath the clamps on the rail of the designed fixator. Additionally, grooves have been created within the rail to prevent directional deviation of the rolling elements. This structure has been designed to provide frictionless or low-friction movement along the rail.

To ensure that ANSYS analyses are performed under appropriate conditions, it is essential to define the connection types and boundary conditions of the designed models prior to conducting the analyses. The ANSYS software offers five contact types: bonded, no separation, rough, frictional, and frictionless [19]. For the LRS-femur model, the contact points between the clamps and the rail were defined using the "no separation" contact type, which allows sliding but prevents separation. The same contact type was applied to the designed fixator-femur model, and the contact points between the clamps and the rail, as well as the areas where the rolling elements make contact with the rail and clamps, were defined accordingly. The remaining contact types were selected as bonded. Additionally, Ti6Al4V alloy was chosen as the material for the fixators. The mechanical properties of the Ti6Al4V alloy and the femur bone are presented in Table 1.

The mesh process of the femur model and fixators, for which contact and material information were entered, was performed. The femur model with 5112 nodes and 2681 elements, the LRS-femur model with 522001 nodes and 293317 elements, and the designed fixator-femur model with 528543 nodes and 296303 elements are shown in Figure 4.

Then, as shown in Figure 5, the femur model and fixators is fixed from its distal section and 750N forces are applied from its head section.

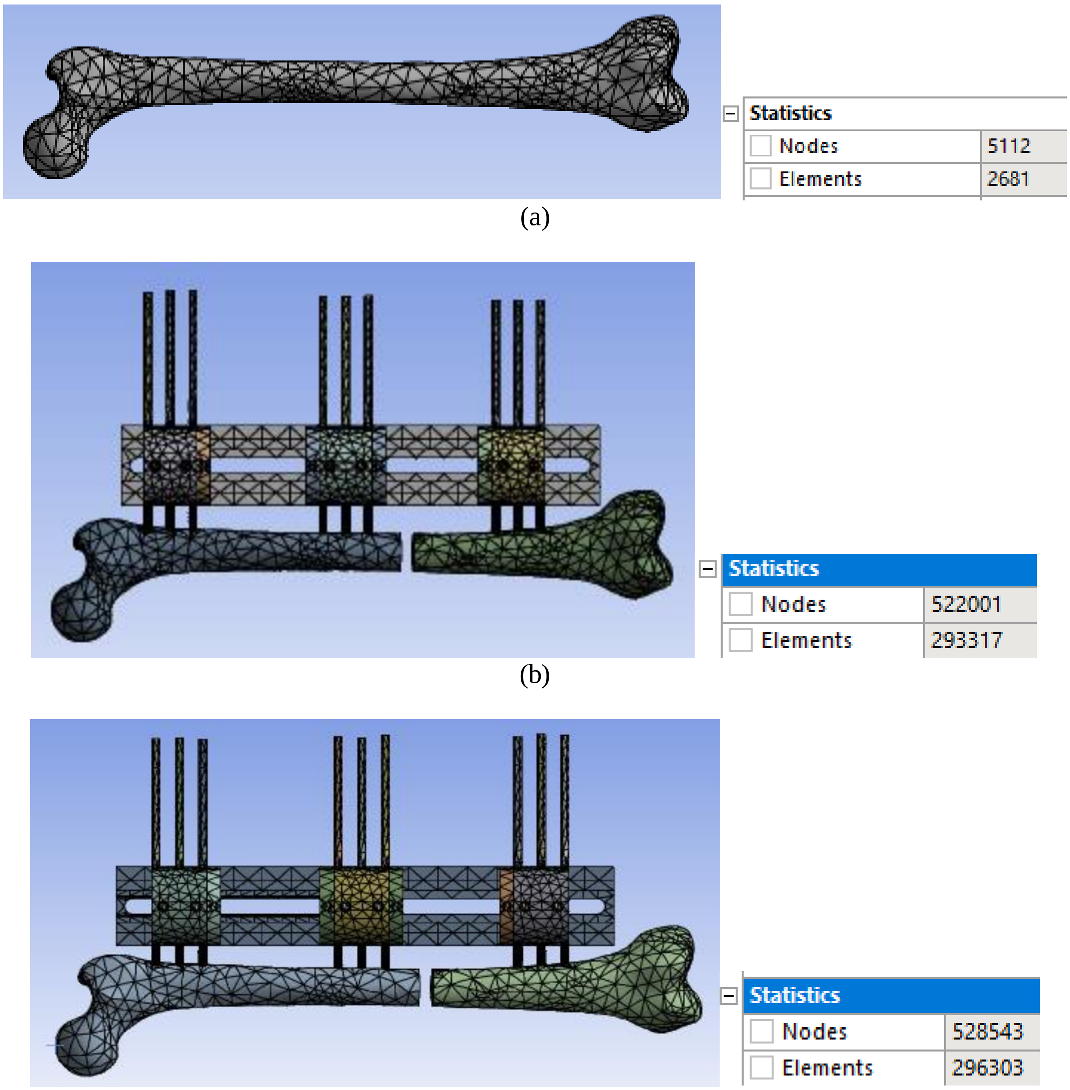
3. Results and Discussion

To evaluate the potential risks that may arise in the designed fixator models and the femur bone more comprehensively, total deformation has been examined. Total deformation measures the extent to which the bone has deformed (such as stretching or bending) due to the applied loads and forces. These parameters play a critical role in identifying the stresses and deformations that could compromise the structural integrity of the bone and fixators. Figure 6 displays the total deformation analysis results for the femur bone, the LRS-femur model, and the designed fixator-femur model.

When examining the deformation distributions, we can observe how deformation is distributed along the bone. The highest deformation is generally observed at the extremities of the structure, particularly in red and orange regions. This indicates that these parts of the bone structure are subjected to greater deformation. In the middle sections and some other areas, deformation is lower and appears in blue and green tones.

Table 1. Mechanical properties of Ti6Al4V alloy and femur bone [5].

Material \ Properties	Ti6Al4V (GPa)	Femur (GPa)
Elasticity Modulus	113,8	17
Poison Ratio	0,342	0,3



Statistics	
☐ Nodes	5112
☐ Elements	2681

(a)

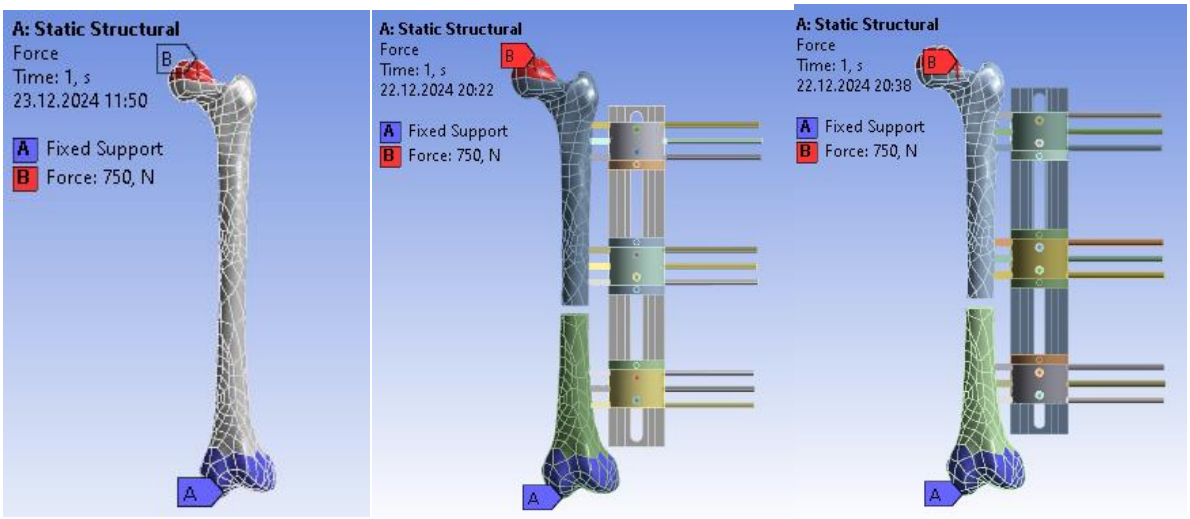
Statistics	
☐ Nodes	522001
☐ Elements	293317

(b)

Statistics	
☐ Nodes	528543
☐ Elements	296303

(c)

Figure 4. Node-element values of a) the femur model b) the LRS-Femur model, c) the designed fixator-femur model.



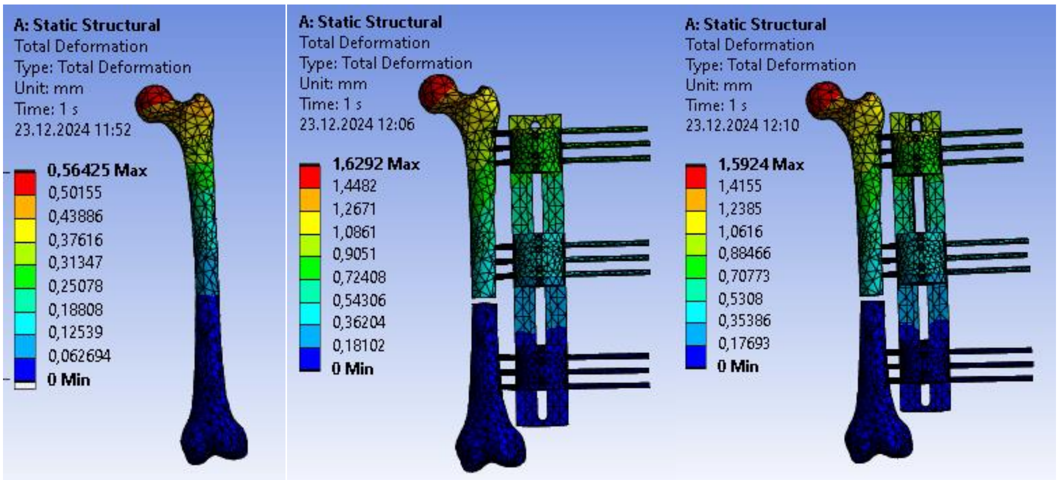
A: Static Structural
Force
Time: 1, s
23.12.2024 11:50
A Fixed Support
B Force: 750, N

A: Static Structural
Force
Time: 1, s
22.12.2024 20:22
A Fixed Support
B Force: 750, N

A: Static Structural
Force
Time: 1, s
22.12.2024 20:38
A Fixed Support
B Force: 750, N

(a) (b) (c)

Figure 5. a) Femur model, b) LRS-femur model, c) Designed fixator – 750N force applied to the femur bone and its fixation



(a) (b) (c)

Figure 6. Total deformation analysis results for a) the femur model, b) the LRS-femur model, and c) the designed fixator.

In the total deformation analysis conducted on the LRS-Femur bone, the regions with minimum deformation are shown in blue, with a value of 0 mm. The regions with maximum deformation are shown in red, with a value of 1.6292 mm. In the total deformation analysis conducted on the designed fixator-Femur bone, the maximum deformation value is 1.5924 mm.

The effect of rolling elements, used in the fixator design to reduce friction, is evident in the analysis. As can be seen from the color scale of the visuals, the new design achieves lower deformation levels, and the high deformation areas (red regions) are reduced. This demonstrates that the use of rolling elements reduces friction in the system and improves the overall stability of the structure.

4. Conclusion

In this study, an advanced fixator system was designed as an alternative to the manually operated fixator. Static analyses were performed for both fixators. According to the analysis results, the advanced fixator system exhibited lower deformation, indicating that it possesses a stiffer structure.

The maximum deformation observed in the manual design indicates that the structure undergoes greater shape changes under load. As seen in the total deformation analysis, this creates potential weak points primarily in the terminal regions of the femur bone. High deformation leads to increased stress concentrations within the material, making these areas more susceptible to fatigue damage over time. Stress concentration can exceed the material's capacity, resulting in the formation of microscopic cracks. These cracks can grow over time and lead to significant damage, potentially causing structural failure.

In the advanced design, the addition of rolling elements reduced friction, thereby decreasing deformation and increasing the stiffness of the structure. The reduction in deformation leads to lower levels of stress concentrations within the system. This strongly indicates that the bearings contribute positively to the structural integrity. Additionally, it demonstrates that the structure undergoes less shape change under load and that deformation is more evenly distributed. This prevents the formation of stress concentrations and thus extends the fatigue life of the material. Such a structure offers significant advantages, particularly in applications requiring long-term durability and reliability.

When comparing the two designs, the maximum deformation value in the manual design is 1.6292 mm, while the addition of rolling elements in the second design reduces this value to 1.5924 mm. This is a significant gain in terms of increasing the material's long-term fatigue resistance and preventing structural failures. The reduction in friction minimizes energy losses during interactions between components, thereby ensuring more efficient operation of the structure.

These analysis results can be used to understand how bone structures behave under specific loads and how supporting elements influence this behavior. Such analyses play a crucial role in orthopedic surgery planning, implant design, and bone repair.

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