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Finite Element Analysis of External Fixation Systems for Open Bone Fractures: A Comprehensive Review

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***Abstract:** External fixation is important for treating open fractures. It helps keep bones stable and protects soft tissues. Finite element analysis (FEA) is used to study how external fixators work. It looks at how they handle weight, how materials behave, and how fractures heal without surgery.*
FEA examines modeling methods, material properties, loading conditions, fixator setups, stress distribution, and patient-specific CT models.
Research shows that the closeness of the fixator, pin setup, and frame shape affect how strong and stable it is. Titanium alloys handle stress better than stainless steel under the same load. Recent studies confirm FEA predictions with real-world and lab results, increasing trust in these models. New trends include using CT scans for patient-specific designs, real-time stress monitoring, and making custom fixators with 3D printing. This review points out research gaps and suggests future studies in both computer models and clinical settings.
Keywords: Finite Element Analysis, External Fixator, Biomechanics, Stress Distribution.

I. INTRODUCTION

Open fractures occur when the skin and soft tissues break, exposing the bone. These are serious bone injuries, often caused by car accidents or falls.

Tibial fractures are the most common type of open long bone fractures. They can lead to infection, improper bone healing, and disability (Kozin et al., 2026; Allen et al., 2025). External fixation is an important method for treating open fractures. This can be a long- or short-term solution.

This method uses pins or wires in the bone, which are held together by a strong frame. It keeps the bone stable without disturbing the blood clot around the fracture.

The fixator needs to be strong but also allow some movement to facilitate healing (Ye et al., 2025; Ng et al., 2025). It is difficult to test the efficacy of fixators using real bones or models because bones and fractures vary. Finite element analysis (FEA) shows how stress affects the fixator and bone. It has become increasingly important in the last ten years (Verma et al., 2024; Chen et al., 2021).

This review examined FEA studies on external fixation for open fractures. It focuses on (1) how FEA models are made, (2) how different fixators perfor.

II. BACKGROUND AND CLINICAL CONTEXT

A. Classification of Open Fractures

The Gustilo-Anderson classification system categorises open fractures based on the wound size, soft tissue damage, and blood vessel issues.

Type I has wounds smaller than 1 cm with minimal contamination. Type IIIC involves large soft tissue loss and damaged arteries that require repair. Fracture grade influences treatment, such as the choice of external fixation (Allen et al., 2025). More severe injuries with more broken pieces and tissue damage require complex, strong fixators. Studies now often examine fracture patterns and severity in detail.

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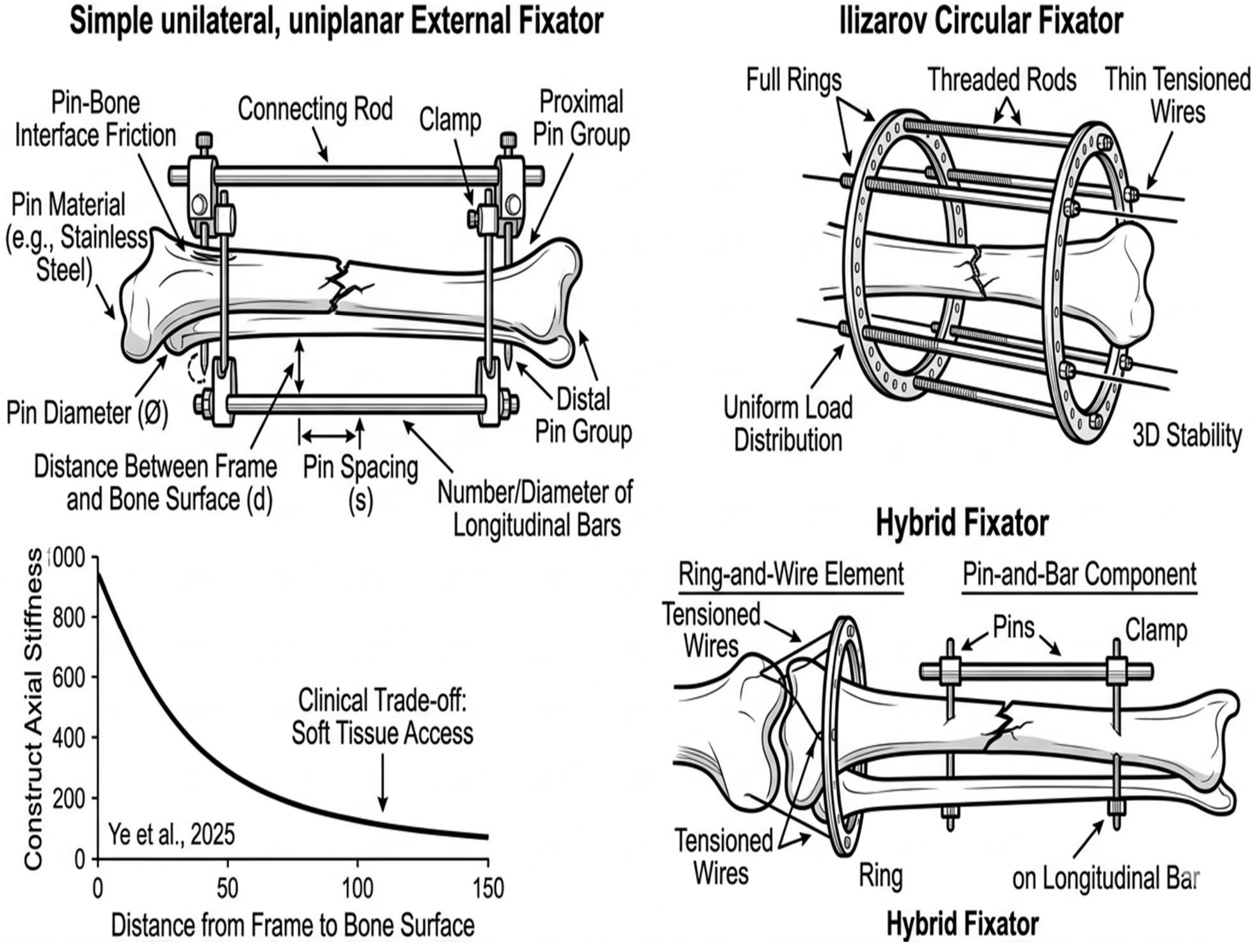
B. Principles of External Fixation



Figuer.1: Schematic overview of unilateral, circular, and hybrid external fixators highlighting structural components and stiffness-related design parameters.

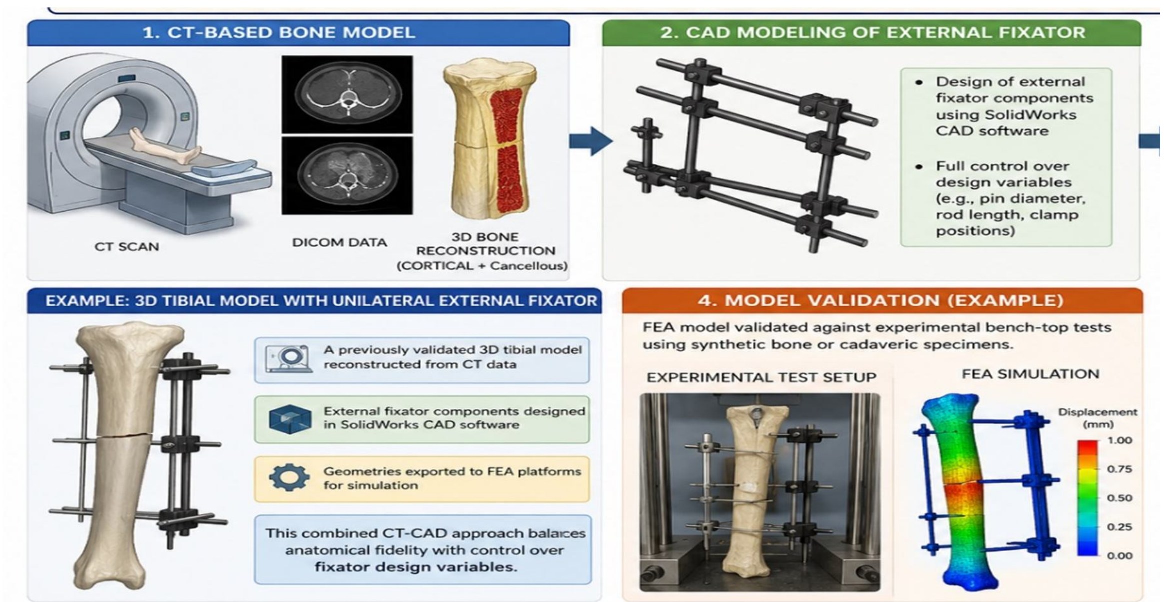
The external fixator helps heal broken bones by holding them in a steady position. It does this with pins, a strong frame, and its shape. Moss and Tejwani (2007) stated that its strength depends on factors such as pin size and material, the distance of the frame from the bone, and the spacing of the pins. These factors affect the handling of different forces. If the rods are closer to the bone, they become stronger, as shown in previous studies (Ye et al., 2025). In real life, when treating open fractures, some space is required between the frame and the skin. The frames can be simple or complex, such as the Ilizarov fixator, which uses rings and rods for better support. This fixator was developed in the 1950s by Gavriil Ilizarov. Hybrid fixators mix ring-and-wire parts near the joints with pin-and-bar parts in the middle of the bone (Abd Aziz et al., 2020).

C. Advances in Finite Element Modeling for Orthopaedic Biomechanical

Finite element analysis (FEA) divides a complex structure into smaller parts with specific material properties. This helps calculate how the structure moves and reacts to the forces. In orthopaedic biomechanics, FEA is used to simulate bone fractures and implant setups that cannot be tested on living people. A reliable FEA model can predict when a structure might fail, help improve implants, and guide surgical decisions (Verma et al., 2024). FEA models for external fixation include components such as bone pieces, fracture areas, pins, wires, clamps, and connectors. Material properties are obtained from experiments or CT scan data in models tailored to patients. The boundary conditions mimic real-life forces, such as compression, bending, and twisting. The type of elements, mesh detail, and interaction between implants and bones affect the model accuracy (Chen et al., 2024; Ye et al., 2025).

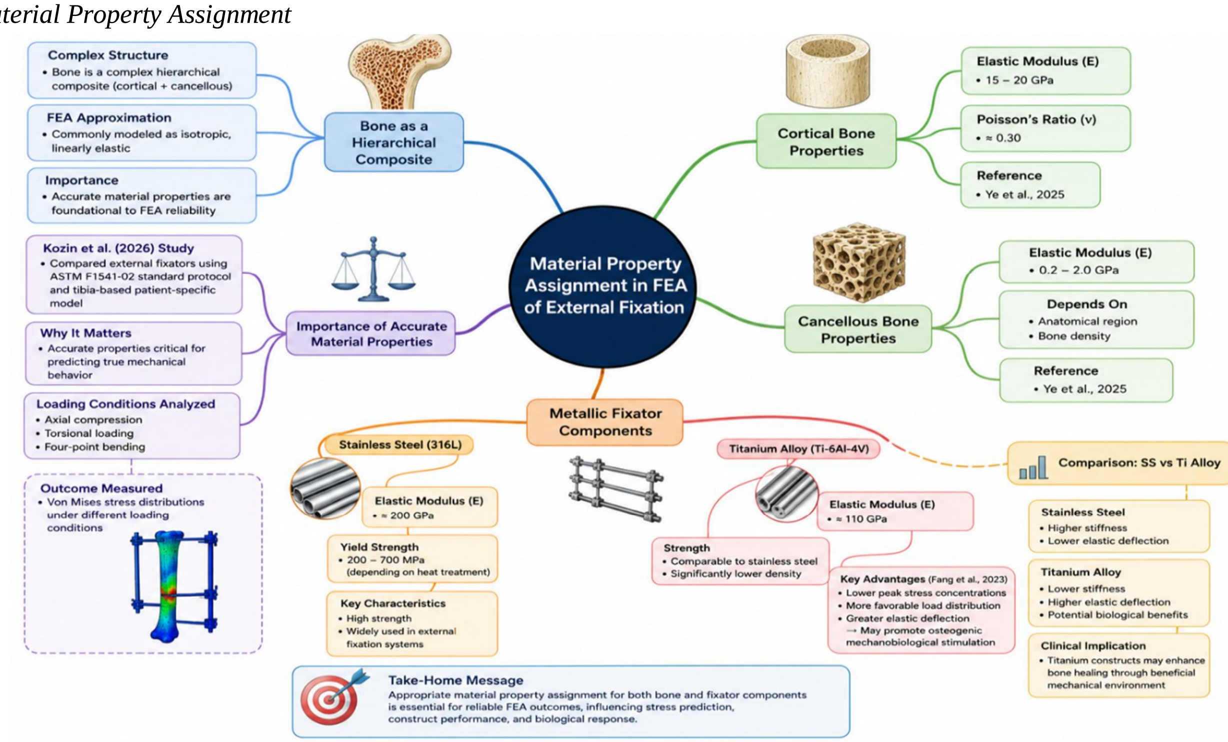
III. METHODOLOGY OF FEA STUDIES: A REVIEW OF APPROACHES

A. Three-Dimensional Geometric Modelling



Recent studies have used 3D models from CT scans or CAD software for external fixation. CT methods create detailed bone shapes by processing DICOM data, showing both the outside and inside of the bones. Ng et al. (2025) used a 3D tibia model from CT scans and designed fixator parts with SolidWorks CAD, and then transferred these designs to FEA platforms. This method combines accurate bone shapes with control over the fixator design. Abd Aziz et al. (2024) confirmed that 3D models for single-sided external fixators in thigh bone fractures match real test results. Validation means checking if the model predictions of movement or stress match physical tests on fake bones or cadavers, with errors allowed between 10-15%.

B. Material Property Assignment



Assigning the correct material properties is crucial for obtaining reliable FEA results. Bone is a complex material but is often treated as having the same properties in all directions and behaving like springs. The cortical bone has an elastic modulus between 15-20 GPa and a Poisson's ratio of 0.30 (Ye et al., 2025). Cancellous bone is softer, with moduli from 0.2-2.0 GPa, which change based on location and density. Kozin et al. (2026) studied external fixators using ASTM F1541-02 and a specific tibia model, highlighting the importance of choosing the appropriate material properties to predict stress under different loads. The properties of metal fixators are well established. Stainless steel (316 L) has an elastic modulus of approximately 200 GPa and a yield strength of 200-700 MPa, depending on the heat treatment. Titanium alloy (Ti-6Al-4V) has an elastic modulus of 110 GPa and similar strength, but is lighter. Fang et al. (2023) found that titanium alloy locking plates reduced peak stress and improved load distribution compared to traditional frames in Type 42A2 fractures. The lower modulus of titanium compared to that of steel allows it to bend more, which may help bone growth.

C. Mesh Generation and Element Types

The mesh density and element type affect the accuracy and cost of the FEA. Ye et al. (2025) used a 2 mm mesh size for most bone and fixator areas. They made it smaller, less than a millimetre, in fracture zones and where implants meet the bone. They used C3D10 ten-node quadratic tetrahedral elements in the Abaqus CAE 2022. Chen et al. (2024) used a 3 mm mesh size overall, with 1 mm size at fixation devices, contact areas, and callus regions. They used first-order tetrahedral elements in the ANSYS Workbench 2022. Mesh convergence studies, which refine the mesh until the stress levels are stable, are recommended but are not always reported in studies.

D. Loading Conditions and Boundary Conditions

FEA models mimic the body's needs during bone healing. They often use axial compression, such as body weight, ranging from 500 N to 1200 N for leg models. Ye et al. (2025) studied tibiofibular fractures with walker-assisted standing to demonstrate early movement. Bending and twisting forces have also been studied; Kozin et al. (2026) used three loading types per ASTM F1541-02 to compare the fixator performance. The boundary conditions held the lower bone end for support and applied force at the upper end. In healing studies, models are changed to show callus growth by altering the fracture zone materials (Chen et al., 2024). This helps predict how stress moves through the fixator and bone as healing progresses, affecting the timing of frame adjustment or removal.

IV. SIGNIFICANT OUTCOMES OF FINITE ELEMENT ANALYSIS STUDIES

A. Effect of Fixator Configuration on Construct Stability

The type of fixator frame affects its efficacy. Ye et al. (2025) studied different fixator setups for tibiofibular fractures using FEA in Abaqus. They found that moving the crossbar 2 cm closer to the bone increased the stability by 21%. For fractures near the top of the tibia, hybrid frames were better than single-sided frames. Single-bar frames with diagonal pins are the best for fractures near the bottom of the tibia.

Ng et al. (2025) examined a new cross-locking rod setup for fractures at the bottom of the tibia. They compared single (Model 2) and double (Model 3) cross-locking with delta and hybrid frame locking. Cross-locking frames using the same pins and rods as the delta frames were stiffer, with double cross-locking being the most stable. These frames are less bulky, aiding recovery after surgery, and the patients healed well. Blažević et al. (2022) compared external locking plates with regular fixation for fractures near the top of the tibia. External locking plates cause less stress at the pin-bone connection, which may result in fewer complications; however, they make it harder to access wounds, limiting their use in severe open fractures.

B. Stress Distribution and Von Mises Stress Analysis

Von Mises stress analysis was used to check whether the implants might break in FEA. It shows the stress at each point in the model. Kozin et al. (2026) studied the Von Mises stress in devices for broken tibias. They used a model based on Indonesian body sizes and the American Society for Testing and Materials F1541-02 protocol. The highest stress was observed when the pins were connected to the clamps and bone when pressure was applied. This matched real cases of pin loosening and problems. The model based on real anatomy showed different stress patterns than the ASTM model, indicating the need for accurate anatomy in assessments. Fang et al. (2023) found that titanium plates for fixing Type 42A2 tibial fractures had lower maximum Von Mises stresses (312 MPa) than traditional frames (498 MPa). This was a 37% reduction because the plate spread the load better than the beam. Titanium also reduces movement at the fracture site, aiding in healing.

C. Unilateral External Fixators for Femoral Fractures
Abd Aziz et al. (2024) did a detailed study using FEA and experiments to check how well a unilateral external fixator works on different types of femoral fractures. They examined three fracture types: subtrochanteric, midshaft, and supracondylar. The fixator worked well for midshaft fractures but showed more stress and bending in subtrochanteric and supracondylar fractures than in midshaft fractures. This suggests that complex femoral fractures near the joints may require additional support or different methods. The study tested synthetic femoral bones and found that the FEA predictions were within 8% of the actual measurements, proving the model's accuracy.

D. Fracture Healing Stage Modelling and Stress Monitoring
A new FEA tool helps understand how broken bones heal by predicting changes as the bone callus grows. Chen et al. (2024) studied bone healing by looking at how stress on an external fixator changes. Their FEA model examined tibia fractures in three stages: early (soft tissue), middle (woven bone), and late (hard bone). They used different material properties at each stage. The results showed that as the callus became stronger, it took more load from the fixator, reducing stress on it. Points sensitive to stress showed good healing progress, suggesting that the use of strain gauges in clinics could provide real-time feedback. Matsuura et al. (2025) expanded this by using patient-specific CT scans in FEA to check bone strength for deciding when to remove the frame. The study found that the bone strength predicted from CT scans matched the actual healing strength. This suggests that removing the frame is safe when the predicted strength is > 50% of that of a healthy bone. This method helps meet a significant clinical need, as current decisions often rely on personal judgment.

E. Ilizarov and Circular Fixator Analysis
The Ilizarov circular fixator uses rings and tight K-wires. Many studies have investigated this using FEA. Liu et al. (2022) studied how the Ilizarov fixator works. They used screw theory to determine how forces move during bone healing. They checked tibia tensions and stresses experimentally. The Ilizarov design shared axial loads well between the wire-ring parts and the bone. The highest stresses at the wire-bone points were safe for the patients. Abd Aziz et al. (2020) compared different fixator setups for thigh bone breaks. They found that the Ilizarov setup spread stress evenly but was bulkier and harder for patients. For open fractures requiring wound access, unilateral or hybrid frames were better, even if they were slightly less stiff.

F. Novel External Fixation Concepts
In recent years, new methods for fixing bones have been developed using FEA. Chen et al. (2025) talked about a method to fix broken shin bones from the outside. This method was more stable than other fixators and functioned well under repeated stress. Bangura et al. (2023) looked at two methods for fixing open fractures in the lower shin. They found that using a locking plate from the outside lowered the infection risk by reducing pin sites while keeping the bone stable, as shown by the FEA. Patients with locking plates had fewer complications.

V. MATERIAL CONSIDERATIONS IN EXTERNAL FIXATOR DESIGN
The materials used for the fixator parts affect their performance, rust resistance, safety, and patient comfort. Common materials include stainless steel (316 L grade), titanium alloys (Ti-6Al-4V), and carbon fibre-reinforced polymer composites. Each material has different properties. Stainless steel is very strong, which is good for heavy loads, but it does not match bone stiffness well, which can cause bone issues. Titanium alloys are less stiff, match the bone better, and cause less stress at the pin-bone connection than stainless steel (Fang et al., 2023; Kozin et al., 2026). Carbon fibre-reinforced polymer (CFRP) composites are beneficial because they are see-through on X-rays, lightweight, and have adjustable stiffness. Studies have shown that CFRP fixators can be as stiff as metal fixators but are lighter and better for MRI scans. However, they are more difficult to fabricate and more expensive, which limits their use.

VI. PIN TRACT COMPLICATIONS AND FEA INSIGHTS
Pin tract infection is a common complication of external fixation. It affects 30-60% of patients, depending on the duration of fixation and the type of fracture. Stress at the pin-bone interface can cause poor bone integration and lead to infection. The FEA helps to understand this problem. Allen et al. (2025) studied pin placement in open fractures. They found that expert opinions are often used because of the lack of strong evidence. Guidelines suggest placing pins away from contaminated areas; however, this is not supported by controlled studies.

The authors recommend further studies using FEA to model stress at different pin-to-wound distances. Cates et al. (2025) examined the fracture risk at pinholes after switching to plate fixation. They tested synthetic tibiae using different screw setups. A plate that bridges the pinhole improves load-bearing, which affects surgical planning for staged management.

VII. PATIENT-SPECIFIC AND CT-BASED FEA

The shift from general to patient-specific CT-based bone models is a major change in the study of fracture healing. These models consider each person's unique bone shape, thickness, and density, which affect how the bones handle stress. Kozin et al. (2026) found that a custom tibia model for Indonesian patients showed different stress patterns compared to a standard model, impacting the testing of external fixators. Matsuura et al. (2025) used CT-based analysis to monitor bone strength over time, showing that strength increases predictably as bones heal. This method can be used in clinical settings, taking 4-6 hours per case with some automated assistance. AI improvements could reduce this time to less than 30 min, allowing faster decision-making with CT-based analysis in the future.

VIII. LIMITATIONS OF CURRENT FEA STUDIES

Despite advancements in finite element analysis (FEA) of the biomechanics of external fixation, several key limitations impede the generalisability and clinical applicability of the findings. Predominantly, FEA studies model the bone as linearly elastic, isotropic, and homogeneous, whereas the bone is inherently viscoelastic, anisotropic, and heterogeneous. This simplification may lead to an underestimation of the stress concentrations and nonlinear deformation under high or cyclic loading conditions. Furthermore, the bone-implant interface is frequently modelled as perfectly bonded or characterised by a single friction coefficient, neither of which adequately captures the complex evolution of osseointegration. Additionally, most studies simulate a single or static loading condition and fail to account for dynamic gait cycles. Patients with open fractures are often mobilised using assistive devices that generate repetitive submaximal loads. Fatigue analysis, which is critical for understanding pin loosening and fixator failure, is rarely conducted. Moreover, soft tissue is typically excluded from FEA models, despite its role in exerting stabilising forces and constraining fragment motion; its omission may lead to overestimation of construct deformations. Few studies have incorporated uncertainty or sensitivity analyses, leaving unresolved questions regarding model predictions under varying material properties or boundary conditions.

IX. EMERGING TRENDS AND FUTURE DIRECTIONS

Recent developments have significantly transformed the application of Finite Element Analysis (FEA) in fracture fixation. Noteworthy advancements include patient-specific modelling, which is facilitated by automated segmentation and cloud-based platforms. Coupled musculoskeletal FEA models now incorporate muscle force predictions. Additionally, artificial intelligence (AI) is used to predict FEA outcomes from imaging data without the need for comprehensive simulations, thereby enabling rapid risk stratification. The 3D printing of patient-specific fixators, as informed by FEA, presents new opportunities. O'Connor et al. (2023) reviewed 3D-printed fixation devices, highlighting their feasibility and mechanical advantages. FEA plays a crucial role in optimising fixators for efficient material usage, reduced weight, and stiffness maintenance. The integration of bioactive coatings, smart materials, and drug-eluting properties into FEA-optimised fixators represents the next generation of fixation technologies. The concept of stress monitoring in external fixators, as proposed by Chen et al. (2024) and validated by Matsuura et al. (2025), has the potential to mitigate issues such as premature removal, re-fracture, and prolonged fixation periods. Future research should focus on establishing stress threshold protocols linked to FEA predictions. Standardising FEA methodologies, including the development of material databases and reporting guidelines, would enhance the comparability and reproducibility of studies in this field.

X. CONCLUSION

Finite element analysis (FEA) plays a crucial role in biomechanical investigations of external fixation in open fractures, facilitating the prediction of stress distribution, fracture stability, and construct rigidity in the bone. The critical factors influencing these outcomes include the proximity of the fixator to the bone, pin configuration, frame geometry, and material selection. Titanium alloys are favoured over stainless steel because of their ability to minimise peak stresses and reduce modulus mismatch. Cross-locking frames demonstrate superior performance for specific fracture types. The use of patient-specific CT models enhances clinical relevance, whereas iterative FEA monitoring assists in evaluating fracture healing. However, limitations persist, such as the linear elastic approximation of bone, exclusion of soft tissue, and absence of dynamic loading conditions. Future research should prioritise the clinical validation of FEA predictions, standardisation of modelling protocols, and development of efficient patient-specific pipelines. The integration of FEA with additive manufacturing and digital health technologies positions computational biomechanics at the forefront of personalised fracture-management research.

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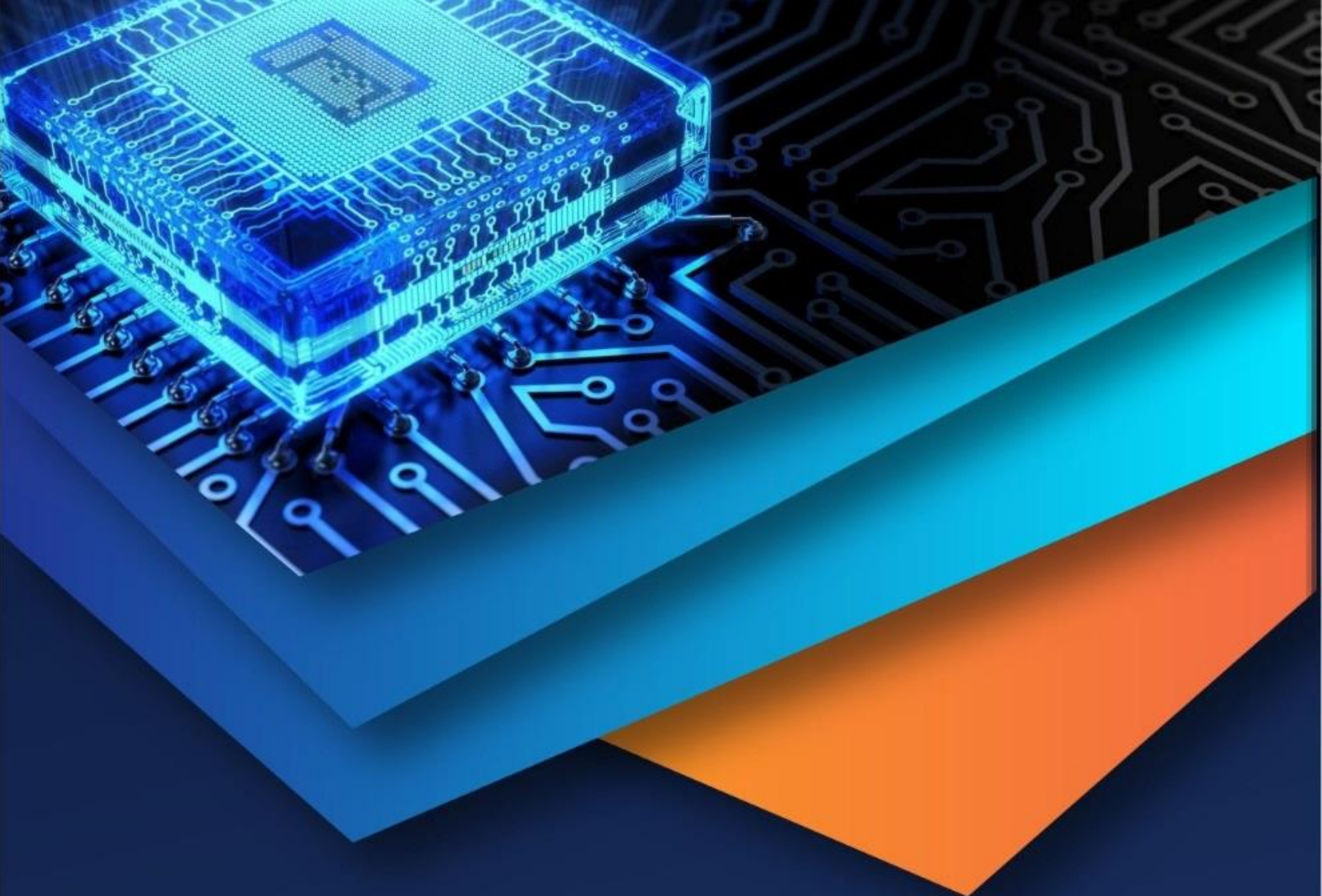

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