**Scientific Reports**

https://doi.org/10.1038/s41598-026-43182-8

**Article in Press**

# Biomechanical evaluation of X-ray permeable CF/PEEK composite versus conventional titanium alloy for tibial external fixation plates: a finite element analysis

**Received: 12 August 2025**

**Accepted: 2 March 2026**

Published online: 14 March 2026

**Cite this article as: Wang S., Zhao Z., An L. *et al.* Biomechanical evaluation of X-ray permeable CF/PEEK composite versus conventional titanium alloy for tibial external fixation plates: a finite element analysis. *Sci Rep* (2026). https://doi.org/10.1038/s41598-026-43182-8**

**Shuaiyi Wang, Zuodong Zhao, Lin An, Ning Ni, Jingwei Zhang, Qing Yan & Jianming Chen**

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

ARTICLE IN PRESS

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

# Biomechanical Evaluation of X-ray Permeable CF/PEEK Composite versus Conventional Titanium Alloy for Tibial External Fixation Plates: A Finite Element Analysis

Shuaiyi Wang [1,2†], Zuodong Zhao [3†], Lin An [1,2], Ning Ni [1,2], Jingwei Zhang [1,2], Qing Yan [4]
Jianming Chen [1,2*]

1. Department of Trauma, Ningbo No.6 Hospital, Ningbo, Zhejiang, China
2. Ningbo Clinical Research Center for Orthopedics, Sports Medicine & Rehabilitation, Ningbo, Zhejiang, China
3. Department of Oral Health Sciences-Orthodontics, KU Leuven and Service of Dentistry, University Hospitals Leuven, Leuven, Belgium.
4. School of Biological and Chemical Engineering, NingboTech University, Ningbo, China

***Corresponding author:**
Jianming Chen
Trauma Orthopedic Center, Ningbo No.6 Hospital Affiliated to Ningbo University, Ningbo, Zhejiang 315040
E-mail: easonnbly@163.com

† Shuaiyi Wang and Zuodong Zhao have contributed equally to the work

**Funding:** Supported by the Agricultural and Social Development Science and Technology Project of Yinzhou District, Ningbo City (2020AS0034); Ningbo No.6 Hospital Science and Technology Program (2023002); Ningbo Clinical Research Center for Orthopedics, Sports Medicine & Rehabilitation (2024L004)

**Data Availability:** The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

# Biomechanical Evaluation of X-ray Permeable CF/PEEK Composite versus Conventional Titanium Alloy for Tibial External Fixation Plates: A Finite Element Analysis

## Abstract

**Objective:**

This study aimed to evaluate the mechanical performance of CF/PEEK composite plates for external fixation through finite element analysis (FEA), and to explore the impact of different screw placement patterns on fixation stability.

**Methods:**

A proximal tibial fracture model treated with external fixation was constructed using FEA. Longitudinal loading was applied to simulate walking stress, with additional internal and external rotational torques to mimic load-bearing movement. Mechanical responses of titanium alloy and CF/PEEK plates were compared under three loading conditions: longitudinal, longitudinal with internal rotation, and longitudinal with external rotation. Screw alignment was also varied between linear and non-linear configurations to assess its biomechanical influence.

**Results:**

Compared to titanium alloy group, the linear CF/PEEK plate exhibited a mild increase in displacement of 0.232–0.386 mm (8.23–11.14%), accompanied by a substantial reduction in plate stress of 46.03–80.84%. At the fracture site, interfragmentary displacement increased slightly by 0.105–0.132 mm (5.56–6.74%), while fracture-site stress increased by 3.119–18.029 MPa (18.30–63.20%). The non-linear CF/PEEK plate demonstrated a similar biomechanical performance, with no significant differences compared with the linear configuration.

**Conclusion:**

For external plate fixation, CF/PEEK represents a promising alternative to conventional titanium alloy plates. By allowing an acceptable level of local micromotion, CF/PEEK plates significantly reduce stress in the plate and screws while increasing stress transfer at the fracture site. This load-sharing behavior may mitigate stress shielding associated with traditional metallic plates and thereby promote early biological fracture healing.

**Key words:** Carbon fiber reinforced polyetheretherketone; External fixation; Finite element; Tibia fracture

## Introduction

Tibial fractures constitute approximately 15-25% of all long bone fractures, with an annual incidence of 17-22 cases per 100,000 population.[1] The clinical significance of these injuries is magnified when complicated by acute compartment syndrome, which occurs in 2-9% of tibial fractures and represents a true orthopedic emergency.[2]

Managing tibial fractures complicated by acute compartment syndrome and/or severe soft-tissue injuryrequires balancing fracture stabilization with soft tissue protection. Traditional plate fixation risks implant exposure through swollen tissues,[3] while external fixators can obstruct wound care and predispose to joint stiffness. This clinical difficulty has driven the exploration of alternative solutions, with emerging evidence suggesting that an external fixation plate system which combines the biomechanical advantages of internal fixation with the soft tissue benefits of external fixation may offer an optimal balance. Such hybrid techniques demonstrate promise in maintaining articular reduction while simultaneously facilitating wound management and simplifying subsequent definitive procedures.[4–6]

Beyond clinical considerations, the biomechanical behavior of externalized plate fixation has been increasingly investigated using experimental testing and finite element analysis. Previous studies on metallic plate-based external fixation constructs have demonstrated that bending stiffness, torsional rigidity, plate–bone offset, and screw configuration are critical determinants of construct stability and interfragmentary motion under axial and rotational loading. These investigations indicate that, even when identical plate geometries are used, variations in material properties and construct design can substantially influence stress distribution within the implant and load transfer to the bone.[7]

Metal plates used for external fixation, while reliable under specific conditions, may exhibit limited torsional rigidity depending on construct configuration and loading conditions.[8] This limitation can lead to clinical risks such as unnecessary patient trauma and the potential for subsequent surgical interventions. Furthermore, the opacity of metal plates complicates post-operative imaging,[9,10] making it difficult for clinicians to accurately monitor the healing process and early detect complications like osteomyelitis. In response to these challenges, Carbon Fiber

Reinforced Polyetheretherketone (CF/PEEK) composites have emerged as a promising alternative. These high-performance polymers exhibit robust physicochemical properties, are X-ray translucent and are MRI compatible, making them ideally suited for both internal and external fixation applications.[11,12]

However, the biomechanical behavior of CF/PEEK composites in the context of external plate fixation remains insufficiently characterized in direct comparison with established metallic systems under combined axial and rotational loading. We hypothesized that, within an identical construct geometry, replacing titanium alloy with CF/PEEK would primarily modify load sharing between the implant and bone by reducing implant stress while increasing mechanical stimulation at the fracture site, rather than fundamentally altering overall construct stability.

This study aims to evaluate the biomechanical feasibility of substituting titanium alloy with CF/PEEK for external plate fixation using finite element analysis, additionally we also intend to assess whether distal screw arrangement (linear vs non-linear) influences construct stability and stress distribution.

## Materials and Methods

A healthy adult volunteer was recruited for this study, following these inclusion criteria: no history of surgery, trauma, tumors, or inflammation on the scanned side, and generally good health, nutrition, and mental state. This study was approved by our institution's ethics committee (Ethical Approval No. K2019053). The volunteer was fully informed about the study and provided written informed consent. All methods were carried out following relevant guidelines and regulations based on the Helsinki Legislation.

### Model Construction

High-resolution CT images of the healthy volunteer's right tibia were obtained using a Siemens SOMATOM Sensation 64 scanner (Siemens Healthineers, Erlangen, Germany) with a slice thickness of 0.5 mm. The image data were stored in Digital Imaging and Communications in Medicine (DICOM) format and imported into Mimics 19.0 (Materialise, Leuven, Belgium) for 3D reconstruction. Bone segmentation was performed using a threshold-based region-growing algorithm. Manual adjustments were applied to ensure anatomical accuracy, particularly in areas of complex geometry. The segmented cortical bone and cancellous bone was then exported as a STL triangular mesh file for further processing. The STL model was subsequently imported into Geomagic Studio 2013 (Geomagic, NC, USA) for surface optimization. Operations including smoothing, wrapping, hole-filling, and surface editing were performed to ensure mesh integrity and suitability for finite element meshing. The average cortical thickness of the tibial plateau is approximately 2.3 mm (1.2–3.5 mm), while that of the tibial shaft averages about 7 mm (4.10–9.88 mm). Using manually identified metaphyseal boundaries, the cancellous bone region was delineated. Because the cancellous bone within the tibial shaft has minimal influence on the mechanical behavior, this region was excluded from the analysis. A 3D model of the osteosynthesis plate was designed based on the distal femoral LISS plate (Synthes GmbH, Switzerland) using the Handyscan 700 3D scanning system (Jiangsu Umeas Measuring Control Technology Co., Ltd., China; accuracy 0.03 mm) and SOLIDWORKS 2009 SP2.1 software (Dassault Systems, Massachusetts, USA). The fracture was simulated at the proximal tibia approximately 10 cm distal to the tibial plateau, characterized as a transverse fracture. The plate was positioned on the medial side of the tibia, parallel to the longitudinal axis of the tibia and 1 cm from the bone surface. Six screws were placed on the proximal side in a dense array, and four screws on the distal side in a spaced arrangement. Two configurations were explored for the distal screws: linear and non-linear arrangements. In the non-linear configuration, each of the four distal screws was shifted anteriorly or posteriorly by half a screw-hole interval (approximately 4.26 mm in the transverse direction), while the screw orientation remained perpendicular to the osteosynthesis plate. The finite element model is shown in **Figure 1.**

### Mesh Convergence Analysis

Mesh convergence analysis was performed to ensure the numerical stability of both displacement and stress results. Meshing was conducted in ANSYS Workbench (Mechanical module) with the physics preference set to “Mechanical” and the element order set to “Program Controlled.” SOLID187 elements (10-node quadratic tetrahedral elements) were automatically selected due to their suitability for complex geometries and quadratic displacement accuracy.

The element sizes for the bone, plate, and screws were set to 2.5 mm, 2.0 mm, and 1.5 mm, respectively, with adaptive sizing applied to ensure smooth mesh transitions. Mesh refinement was evaluated by reducing the bone mesh size from 3.0 mm to 2.5 mm. Under this refinement, the relative change in global displacement was +0.93%, while the corresponding variation in von Mises stress was −1.02%. Both values were below 2%, indicating that further mesh refinement had a negligible influence on the computed mechanical responses. Based on this convergence assessment, the final finite element model consisted of 113,249 elements and 207,315 nodes, providing an effective balance between computational efficiency and analytical precision. This convergence assessment strategy is consistent with previously reported finite element studies evaluating convergence based on relative changes in mechanical response metrics between adjacent mesh densities.[13]

## Material Parameters

In this study, the CF/PEEK component was modeled as an orthotropic material, with transverse and longitudinal Young's moduli of 3.6 GPa and 18.0 GPa, respectively, based on previously published experimental and finite element studies of CF/PEEK orthopedic implants.[14] All other materials were modeled as linear elastic and isotropic. For the tibia, a Young's modulus of 16.8 GPa and a Poisson's ratio of 0.3 were assigned to cortical bone, while cancellous bone was assigned a Young's modulus of 0.15 GPa and a Poisson's ratio of 0.2.[15] Titanium alloy was assigned a Young's modulus of 110 GPa and a Poisson's ratio of 0.34. The material parameters used in the calculations are listed in **Table 1**.

## Boundary and Load Conditions

The lower surface nodes of the tibia shaft were fixed, constraining all six degrees of freedom. A distributed load of 2230 N, simulating the body weight, and an 8 Nm torque, simulating normal adult torsional stress during vertical loading and internal-external rotation, were applied to the upper joint surface of the tibia.[16] Although these loading magnitudes exceed those typically used to represent immediate post-operative partial weight-bearing, they were intentionally selected to represent a high-demand mechanical scenario, allowing assessment of construct stability and load-sharing behavior under more challenging conditions.[16] Three loading scenarios were simulated: Longitudinal load only, longitudinal load combined with internal rotational torque, and longitudinal load combined with external rotational torque. The biomechanical testing of the fracture fixation model was conducted using ANSYS 18.0 (ANSYS Inc., Canonsburg, PA, USA). All simulations were performed using a static structural analysis in ANSYS. For the contact definitions, a friction coefficient of 0.3 was assigned to the fracture interface, while all other interfaces were defined as bonded.[17,18] A detailed summary of all contact interfaces and corresponding contact assumptions is provided in **Table 2.**

## Results

After substituting titanium alloy with CF/PEEK composite material for the osteosynthesis plate, changes were observed in the maximum displacement and von Mises stress of the plate, screws, tibia, and fracture site under different loading conditions. (**Table 3-5**)

For the linear CF/PEEK configuration, all displacement values increased compared with the control group: tibial displacement increased by 0.35–0.487 mm (9.7–12.16%), plate displacement by 0.232–0.394 mm (8.23–11.14%), and screw displacement by 0.278–0.421 mm (8.91–11.72%). In contrast, stresses in the plate and screws decreased markedly, with reductions of46.03–80.84% in plate stress and 22.32–34.30% in screw stress.

For the non-linear CF/PEEK configuration, tibial displacement increased by 0.365–0.487 mm (9.97–12.16%), plate displacement by 0.241–0.401 mm (8.55–11.34%), and screw displacement by 0.287–0.428 mm (9.20–11.92%) compared with the control group. Plate stresses were reduced by 59.80–66.19%, and screw stresses by 26.48–35.90%.

At the fracture site, in the linear CF-PEEK configuration, the interfragmentary displacement increased slightly by 0.105-0.132 mm (5.56–6.74%), and the fracture-site stress increased by 3.119-18.029 MPa (18.30-63.20%) across loading modes. In the non-linear configuration, interfragmentary displacement increased by 0.109-0.132 mm (5.78-6.74%), and fracture-site stress increased by 3.124–16.955 MPa (18.33–61.26%). Paired t-tests demonstrated no statistically significant differences between either CF/PEEK configuration and the titanium control group in terms of displacement or stress changes ($P > 0.05$).

**Figures 2 and 3** illustrate the displacement contour maps of each fracture model under axial, combined axial-internal rotation, and combined axial-external rotation loading. **Figure 4** presents the stress and displacement contour maps at the fracture site for the three models under longitudinal loading and combined longitudinal-internal or -external rotational loading, allowing a direct comparison of construct stability at the fracture interface. Overall, CF/PEEK was associated with modest increases in displacement, accompanied by reduced implant stress and increased stress values at the fracture interface.

It is noteworthy that the distributions of stress and displacement exhibited pronounced local characteristics. Under internal rotational loading (**Figure 3A–C)**, the titanium plate group showed evident stress concentration at the medial aspect of the two proximal-adjacent screws, whereas the CF/PEEK plate group demonstrated a more uniform stress distribution across all screws, with markedly reduced peak stress values (**Table 4**). At the fracture site (**Figure 4**), the CF/PEEK plate group exhibited stress contour patterns in which higher stress was more concentrated around the central region of the fracture line under both longitudinal and combined rotational loading, whereas in the titanium plate group, stress was more diffusely distributed around the screw holes at both ends of the plate. In addition, the CF/PEEK group showed a steeper displacement gradient at the fracture gap, as reflected by the broader warm-colored regions in the displacement contours (**Figure 4**), indicating increased local micromotion. This observation is consistent with the relative displacement results reported in **Table 5**, where CF/PEEK constructs generally exhibited higher interfragmentary displacement compared with the titanium group.

## Discussion

The treatment of open tibial fractures presents a multifaceted challenge in modern trauma orthopedics. Epidemiological data indicate that such injuries are associated with a 6.8% risk of nonunion and influenced by over 15 independent risk factors that collectively modulate the healing process.[19] Among these, open wounds and infection significantly elevate the complexity of management. In current clinical practice, approximately 38% of cases require delayed internal fixation due to severe soft tissue damage or compartment syndrome.[20] This necessary compromise in surgical strategy results in a prolonged hospital stay (4.2 ± 2.1 days) and an additional 23% increase in healthcare costs.[21]

While traditional external fixation offers temporary stability, its clinical utility is significantly limited by several drawbacks, including excessive weight, and an impairment in activities of daily living. To address these limitations, researchers have investigated externalized internal fixation plates as an alternative approach, which has shown reliable clinical outcomes. Recent studies have increasingly focused on the biomechanical properties of externalized internal fixation plates, with accumulating evidence supporting their feasibility and effectiveness.[22,23]

In an in vitro biomechanical study, Su et al. compared three external fixation modalities for tibial fracture management: tibial locking compression plate (LCP), distal femoral LCP, and a conventional external fixator. Their results demonstrated that, when used as an external fixator, the distal femoral LCP provided superior biomechanical stability and adjustability compared to both the tibial LCP and traditional external fixators, particularly for distal tibial fractures. The authors also emphasized the importance of implant positioning in optimizing fixation stability, specifically plate orientation and screw angulation.[24] Further clinical validation was provided by Makelov et al.,[25] who treated 18 patients with high-energy unstable tibial metaphyseal fractures using single-stage external fixation with a distal femoral LCP. At a mean follow-up of 21.4 ± 12.3 months, 94% of patients achieved fracture union without complications such as infection or fixation failure. The study concluded that, with appropriate patient selection and adherence to standardized rehabilitation protocols, externalized internal plate fixation can offer sufficient stability and favorable clinical outcomes, representing a viable alternative to conventional external fixation for managing unstable tibial metaphyseal fractures.

Previous finite element and experimental studies have systematically evaluated the biomechanical performance of metallic locking plates used as external fixators. These studies consistently report that, compared with conventional unilateral external fixators, externalized locking plates generally exhibit higher overall stability and reduced construct displacement under axial compression, bending, and torsional loading. Their mechanical behavior is strongly influenced by plate–bone offset, screw distribution, and construct configuration.[26,27] In the present study, the biomechanical response of the titanium alloy control model was in close agreement with these previously reported findings, supporting the validity of the finite element modeling approach adopted for external plate fixation. Building on this established framework, we further investigated the effect of material substitution by replacing titanium alloy with CF/PEEK while maintaining identical geometry and boundary conditions. Compared with prior studies focusing primarily on geometric or configurational optimization of metallic external plates, our results demonstrate that CF/PEEK plates preserve construct stability while exhibiting a more pronounced load-sharing behavior, characterized by reduced implant stress and increased stress transfer to the fracture site. In addition, recent finite element and experimental investigations of novel external fixation systems suggest that further improvements in mechanical performance can be achieved through optimization of plate morphology and structural design.[28] Taken together, these findings indicate that, in addition to construct design optimization, the introduction of composite materials with elastic moduli closer to that of bone may represent a complementary strategy for biomechanical enhancement of external plate fixation systems.

However, traditional fixation devices are made by metal. In our clinical follow-up, we observed that commonly used metallic fixation devices tend to obscure the fracture site, interfering with the evaluation of fracture healing. This limits the ability to achieve postoperative, data-driven assessment of bone union.[29] Additionally, such devices hinder early radiological diagnosis of complications such as osteomyelitis, and restrict timely guidance on early weight-bearing rehabilitation for patients.[30,31] To address these limitations, we propose the use of carbon fiber-reinforced polyetheretherketone (CF/PEEK) composite materials as an alternative for external fixation plates. Our finite element analysis (FEA) provides the first systematic biomechanical evidence supporting the use of CF/PEEK (carbon fiber–reinforced polyetheretherketone) materials in this novel application.

Carbon fiber-reinforced polyetheretherketone (CF/PEEK) composites possess inherent radiolucency and MRI compatibility,[32] making them advantageous for imaging-based clinical applications. Preliminary studies have explored their use in various fields, including oral and maxillofacial surgery, spinal oncology, internal fixation for traumatic fractures and bone defects, as well as in joint arthroplasty. Accumulating evidence suggests that CF/PEEK implants outperform traditional metallic implants in terms of biomechanical structure, clinical outcomes, and safety profiles.[33–36]

From a mechanical standpoint, CF/PEEK composites exhibit a distinct load-sharing behavior compared with conventional titanium alloy plates. In this study, CF/PEEK was modeled as a linear elastic orthotropic material. Previous studies have shown that CF/PEEK composites typically exhibit linear elastic behavior at strains below approximately 1.0–1.5%, with reported yield strengths exceeding 200 MPa depending on fiber content and orientation.[37,38] In the present analysis, the maximum stress observed in the CF/PEEK plates ranged from 18.5 to 53.9 MPa across all loading conditions, which is well below the reported yield strength. This indicates that the material remained within its linear elastic regime with a sufficient safety margin, and that the predicted displacement and stress responses are not influenced by material nonlinearity. In the present study, fracture models stabilized with CF/PEEK plates showed a moderate increase in overall displacement (approximately 8–12%) relative to titanium constructs, while stresses in the plate and screws were substantially reduced, with plate stress reductions reaching up to approximately 80%. This redistribution of load suggests that CF/PEEK plates transfer a greater proportion of stress to the fracture site, rather than concentrating it within the fixation hardware. This advantage arises from the multiscale architecture provided by carbon fibers embedded within the PEEK matrix. While unreinforced PEEK exhibits an elastic modulus of only 3–4 GPa, well below that of human cortical bone.[37] CF-PEEK composites, particularly those with ~30 wt% carbon fiber, can attain a Young's modulus of approximately 18 GPa, closely approximating cortical bone stiffness and substantially mitigating stress-shielding concerns.[38,39] Notably, both linear and non-linear screw configurations demonstrated comparable biomechanical performance in the revised model, with no statistically significant differences in displacement or stress outcomes. While combined axial and rotational loading increased overall mechanical demand on the construct, the observed changes remained within acceptable ranges for both configurations. These findings suggest that, within the scope of the present finite element analysis, the mechanical behavior of CF/PEEK external plate fixation is appears to be more strongly influenced by material properties than by screw alignment within the configurations tested. Together, these results highlight the importance of considering the coupled effects of material characteristics and structural design when developing next-generation external fixation systems.

In the context of fracture healing, the increased interfragmentary displacement observed in the CF/PEEK models can be interpreted as controlled micromotion rather than mechanical instability. According to classical interfragmentary strain theory,[40] indirect fracture healing is promoted when strain remains below approximately 30%. Based on the simulated fracture-site displacement (0.105–0.132 mm) equals to (18.3–63.2%), the resulting strain remains within this favorable range, suggesting that the micromotion permitted by CF/PEEK plates is biomechanically acceptable and may help reduce stress shielding by enhancing load transfer to the fracture site. However, the clinical relevance of these findings should be interpreted in conjunction with specific fracture characteristics, including fracture pattern, quality of reduction, bone quality, and patient activity level. In particular, in the presence of bone defects, osteoporosis, or suboptimal reduction, stress concentration at the fracture site may increase the risk of secondary displacement or fixation failure. The “acceptable micromotion” provided by CF/PEEK plates should therefore be regarded as a conditional advantage, the effectiveness of which depends on the local fracture environment and the stage of healing. Future studies incorporating animal models or clinical follow-up are warranted to further elucidate the dynamic influence of CF/PEEK plates on the mechanical environment at the fracture site throughout different phases of healing, thereby optimizing their clinical application.

Beyond its mechanical advantages, CF/PEEK also demonstrates excellent biological compatibility. Micro-CT analyses have revealed that 3D-printed CF/PEEK structures with regular pore sizes of 300–500 μm achieved a bone in-growth rate of 65 ± 7%, significantly higher than that observed with conventional metallic implants (42 ± 5%). Moreover, the material’s radiolucency facilitated more accurate postoperative monitoring: callus formation could be assessed with 91.3% accuracy within six weeks, compared to 67.5% in the metal fixation group which is a statistically significant improvement.[41–43]

More importantly, recent advancements in laser direct writing (LDW) technology have enabled the integration of conductive features directly onto CF/PEEK implant components, allowing them to function as embedded strain sensors. These integrated sensor networks facilitate realtime monitoring of micro-strain changes at the fixation site, supporting the concept of "intelligent fixation" and opening new possibilities for individualized rehabilitation protocols and personalized treatment strategies thereby advancing the field of smart orthopedics.[44]

In the present study, a simplified transverse fracture model with direct interfragmentary contact was adopted. This modeling choice was intentional and aligned with the primary objective of the study, which was to evaluate the initial stability and load-sharing characteristics of CF/PEEK composite plates used for external fixation, rather than to replicate the full spectrum of fracture instability. By assuming ideal reduction without segmental bone loss and applying a frictional contact at the fracture interface, this model represents a "critically stable" postoperative condition, in which the fixation system is required to maintain alignment and resist secondary micromotion rather than to bridge large defects or comminuted zones. Although compression and friction at the fracture interface may partially counteract applied torsional loads, this condition reflects a clinically relevant scenario in early emergency fixation, where achieving satisfactory reduction and provisional stability is often the primary goal. Under this assumption, the analysis effectively characterizes the lower bound of torsional resistance necessary to preserve fracture alignment. Although fracture models incorporating explicit interfragmentary gaps or comminution are more representative of highly unstable fractures and may yield higher absolute displacement values. However, the simplified model employed here allows a controlled comparison of different plate materials and screw configurations by minimizing confounding variables related to fracture morphology. Consequently, while the absolute values of displacement and stress should be interpreted within this modeling context, the comparative trends observed between CF/PEEK and titanium constructs remain meaningful. Future studies incorporating gap or comminuted fracture models are warranted to further extend these findings to more severe clinical scenarios.

Several limitations of this study should be acknowledged. First, the screw-plate and screw-bone interfaces were modeled as bonded. This assumption was adopted in accordance with previous external fixation studies and to ensure identical fixation conditions between the control and experimental groups, thereby isolating the effect of plate material as the primary variable. Nevertheless, the interaction between CF/PEEK plates and metallic screws warrants further investigation. Several optimization strategies, such as embedded metallic threads and screw sleeves within PEEK-based plates, have been reported and may substantially improve fixation performance. Given the external fixation application considered in this study, the screw-plate interface offers considerable potential for further mechanical optimization and will be a key focus of future research.

In addition, although CF/PEEK exhibits an elastic modulus closer to that of cortical bone compared with titanium alloys, this material property alone does not directly translate into the overall stiffness of an external fixation system. The mechanical behavior of external plate fixation is strongly influenced by construct geometry, plate-bone offset, and screw configuration. Therefore, the present finite element analysis should be interpreted as a material-level comparison under a fixed geometric configuration, rather than as a validation of the clinical feasibility or superiority of externalized internal fixation plates. Additionally, this study was based on a single healthy tibial geometry to enable a controlled comparison of plate material and screw configuration. While this approach facilitates the evaluation of relative biomechanical trends, it limits the direct extrapolation of absolute displacement and stress values to patients with different bone quality, anatomy, or fracture patterns. Furthermore, the fracture model represents a simplified transverse configuration without callus formation, and the applied loads were intentionally selected as a high-demand test scenario rather than to simulate immediate post-operative loading. While this approach enables a controlled comparison of fixation constructs under challenging mechanical conditions, it does not capture the evolving biomechanics during fracture healing. Therefore, although the comparative trends between materials and screw configurations remain informative, the absolute values of displacement and stress should be interpreted within this modeling context. Finally, the fibula and surrounding soft tissues were not included in the model, and time-dependent changes associated with callus formation were not simulated. As early fracture healing is highly sensitive to the mechanical environment, the effects of increased stress transfer at the fracture site should be interpreted cautiously. Future studies incorporating progressive healing models, additional anatomical structures, and experimental or clinical validation are warranted.

## Conclusion

Compared with conventional titanium alloy plates of identical geometry, CF/PEEK composite plates used for external plate fixation demonstrate a favorable load-sharing behavior. By allowing an acceptable degree of local micromotion, CF/PEEK plates significantly reduce stress in the plate and screws while increasing stress transfer at the fracture site. This mechanical response may alleviate stress shielding associated with metallic plates and thereby potentially supporting early biological fracture healing. Within the limitations of this finite element study, both linear and non-linear CF/PEEK configurations, with screws oriented perpendicular to the plate, exhibited comparable biomechanical performance to titanium constructs, with no statistically significant differences in displacement or stress outcomes. These findings suggest that CF/PEEK represents a promising alternative material for external plate fixation, providing sufficient mechanical stability while offering potential biological advantages. Further experimental validation and optimization of the screw-plate interface are warranted to support future clinical translation.

## Reference

1. Court-Brown CM, Caesar B. Epidemiology of adult fractures: A review. Injury [Internet]. 2006 Aug 1 [cited 2025 Jul 31];37(8):691–7. Available from: https://www.sciencedirect.com/science/article/pii/S0020138306003238?via%3Dihub
2. Cong B, Zhang H. Acute compartment syndrome in tibial fractures: a meta-analysis. BMC Musculoskelet Disord [Internet]. 2025;26(1):329. Available from: https://doi.org/10.1186/s12891-025-08586-z
3. Yoon YC, Kim YJ, Oh CW, Kim HJ, Sim SB, Son SW, et al. Staged Fixation with Respect to Soft Tissue in Tibial Plateau Fractures with Acute Compartment Syndrome: Correlation Analysis of Complications. Clin Orthop Surg. 2024 Dec 1;16(6):854–62.
4. Gaudinez RF, Mallik AR, Szporn M. Hybrid External Fixation of Comminuted Tibial Plateau Fractures. Clin Orthop Relat Res [Internet]. 1996;328. Available from: https://journals.lww.com/clinorthop/fulltext/1996/07000/hybrid_external_fixation_of_comminuted_tibial.32.aspx
5. Tripathy SK, Varghese P, Panigrahi S, Panda BB, Srinivasan A, Sen RK. External fixation

versus open reduction and internal fixation in the treatment of Complex Tibial Plateau Fractures: A systematic review and meta-analysis. Acta Orthop Traumatol Turc. 2021 Sep 1;55(5):444–56.

6. Janssen SJ, Kloen P. Supercutaneous locking compression plate in the treatment of infected non-union and open fracture of the leg. Arch Orthop Trauma Surg [Internet]. 2022;142(11):3201–11. Available from: https://doi.org/10.1007/s00402-021-04104-7
7. Bologna FA, Audenino AL, Terzini M. Bone Plates Runout Prediction Through Tensile Strength and Geometric Properties for Regulatory Mechanical Testing. Ann Biomed Eng [Internet]. 2024;52(2):239–49. Available from: https://doi.org/10.1007/s10439-023-03363-2
8. Egol KA, Kubiak EN, Fulkerson E, Kummer FJ, Koval KJ. Biomechanics of Locked Plates and Screws. J Orthop Trauma [Internet]. 2004;18(8). Available from: https://journals.lww.com/jorthotrauma/fulltext/2004/09000/biomechanics_of_locked_plates_and_screws.3.aspx
9. Zhang Shiling, Patel Dharmesh, Brady Mark, Gambill Sherri, Theivendran Kanthan, Deshmukh Subodh, et al. Experimental testing of fracture fixation plates: A review. Proc Inst Mech Eng H [Internet]. 2022 Aug 3;236(9):1253–72. Available from: https://doi.org/10.1177/09544119221108540
10. Stoffel K, Dieter U, Stachowiak G, Gächter A, Kuster MS. Biomechanical testing of the LCP – how can stability in locked internal fixators be controlled? Injury [Internet]. 2003 Nov 1 [cited 2025 Jul 31];34(SUPPL. 2):11–9. Available from: https://www.sciencedirect.com/science/article/pii/S0020138303003796?via%3Dihub
11. Kurtz SM, Devine JN. PEEK biomaterials in trauma, orthopedic, and spinal implants. Biomaterials [Internet]. 2007 Nov 1 [cited 2025 Jul 31];28(32):4845–69. Available from: https://www.sciencedirect.com/science/article/pii/S0142961207005467?via%3Dihub
12. Hu Z, He J, Chen W, Liu W, Ding J, He C, et al. High-performance carbon fiber reinforced polyether-ether-ketone composite pellets 3D-Printed via screw-extrusion additive manufacturing. Compos Sci Technol [Internet]. 2024 Feb 8 [cited 2025 Jul 31];246:110362. Available from: https://www.sciencedirect.com/science/article/pii/S0266353823004566?via%3Dihub
13. Andrea Bologna F, Elena N, Bentivoglio D, Aprato A, Terzini M, Bignardi C, et al. In Silico Evaluation of the Primary Stability of Acetabular Revision Cups: Standard Versus Locking Screws. J Biomech Eng [Internet]. 2025 Mar 28;147(5). Available from: https://doi.org/10.1115/1.4068226
14. Ceddia M, Pesare E, Solarino G, Lamberti L, Trentadue B. Biomechanical Comparison of Titanium and CFR-PEEK Intramedullary Nails Using Finite Element Analysis. Journal of Composites Science. 2025 Nov 1;9(11).
15. Beirami S, Nikkhoo M, Hassani K, Karimi A. A comparative finite element simulation of locking compression plate materials for tibial fracture treatment. Comput Methods Biomech Biomed Engin [Internet]. 2021 Sep 7;24(10):1064–72. Available from: https://doi.org/10.1080/10255842.2020.1867114
16. Zhang J, Ebraheim N, Li M, He X, Schwind J, Liu J, et al. External fixation using locking plate in distal tibial fracture: a finite element analysis. European Journal of Orthopaedic Surgery & Traumatology [Internet]. 2015;25(6):1099–104. Available from:

https://doi.org/10.1007/s00590-015-1604-7

17. Ng BW, Abdul Wahab AH, Abdul Wahid AM, Abdullah NNAA, Abdul Kadir MR, Ammarullah MI, et al. Finite element analysis and clinical evaluation of cross locking external fixator configuration for distal third tibia fracture. Sci Rep [Internet]. 2025;15(1):13310. Available from: https://doi.org/10.1038/s41598-025-97090-4
18. Ye X, Luo J, Chen P, Wei X, Liu S. Finite element analysis of the stability of tibiofibular fractures treated with various combinations of external fixators. BMC Musculoskelet Disord [Internet]. 2025;26(1):304. Available from: https://doi.org/10.1186/s12891-025-08530-1
19. Tian R, Zheng F, Zhao W, Zhang Y, Yuan J, Zhang B, et al. Prevalence and influencing factors of nonunion in patients with tibial fracture: systematic review and meta-analysis. J Orthop Surg Res [Internet]. 2020;15(1):377. Available from: https://doi.org/10.1186/s13018-020-01904-2
20. Ye Z, Zhao S, Zeng C, Luo Z, Yuan S, Li R. Study on the relationship between the timing of conversion from external fixation to internal fixation and infection in the treatment of open fractures of extremities. J Orthop Surg Res [Internet]. 2021;16(1):662. Available from: https://doi.org/10.1186/s13018-021-02814-7
21. Schmidt AH. The Impact of Compartment Syndrome on Hospital Length of Stay and Charges Among Adult Patients Admitted With a Fracture of the Tibia. J Orthop Trauma [Internet]. 2011;25(6). Available from: https://journals.lww.com/jorthotrauma/fulltext/2011/06000/the_impact_of_compartment_syndrome_on_hospital.7.aspx
22. Ahmad MA, Sivaraman A, Zia A, Rai A, Patel AD. Percutaneous locking plates for fractures of the distal tibia: Our experience and a review of the literature. Journal of Trauma and Acute Care Surgery [Internet]. 2012;72(2). Available from: https://journals.lww.com/jtrauma/fulltext/2012/02000/percutaneous_locking_plates_for_fractures_of_the.53.aspx
23. Zhang J, Ebraheim NA, Li M, He X, Liu J, Zhu L, et al. External Fixation Using a Locking Plate: A Reliable Way in Treating Distal Tibial Fractures. J Orthop Trauma [Internet]. 2015;29(11). Available from: https://journals.lww.com/jorthotrauma/fulltext/2015/11000/external_fixation_using_a_locking_plate__a.15.aspx
24. Su H, Zhong S, Ma T, Wu W, Lu Y, Wang D. Biomechanical study of the stiffness of the femoral locking compression plate of an external fixator for lower tibial fractures. BMC Musculoskelet Disord [Internet]. 2023;24(1):39. Available from: https://doi.org/10.1186/s12891-023-06150-1
25. Makelov B, Mischler D, Varga P, Apivatthakakul T, Fletcher JWA, Veselinov D, et al. Single-Stage Externalized Locked Plating for Treatment of Unstable Meta-Diaphyseal Tibial Fractures. J Clin Med. 2023 Feb 1;12(4).
26. Blažević D, Kodvanj J, Adamović P, Vidović D, Trobonjača Z, Sabalić S. Comparison between external locking plate fixation and conventional external fixation for extraarticular proximal tibial fractures: a finite element analysis. J Orthop Surg Res. 2022 Dec 1;17(1).
27. Fang S, Zhang L, Yang Y, Wang Y, Guo J, Mi L. Finite element analysis comparison of Type 42A2 fracture fixed with external titanium alloy locking plate and traditional external fixation frame. J Orthop Surg Res. 2023 Dec 1;18(1).

28. Liu S, Liang X, Liu S, Guo Z, Wei X, Liang Y. A novel external fixation for treating tibial fractures: a finite element and biomechanical study. J Orthop Surg Res. 2025 Dec 1;20(1).
29. Fisher JS, Kazam JJ, Fufa D, Bartolotta RJ. Radiologic evaluation of fracture healing. Skeletal Radiol [Internet]. 2019;48(3):349–61. Available from: https://doi.org/10.1007/s00256-018-3051-0
30. Govaert GAM, Kuehl R, Atkins BL, Trampuz A, Morgenstern M, Obremskey WT, et al. Diagnosing Fracture-Related Infection: Current Concepts and Recommendations. J Orthop Trauma [Internet]. 2020;34(1). Available from: https://journals.lww.com/jorthotrauma/fulltext/2020/01000/diagnosing_fracture_related_infection__current.3.aspx
31. Flowers DW, McCallister E, Christopherson R, Ware E. The Safety and Effectiveness of Early, Progressive Weight Bearing and Implant Choice after Traumatic Lower Extremity Fracture: A Systematic Review. Vol. 9, Bioengineering. MDPI; 2022.
32. Panayotov IV, Orti V, Cuisinier F, Yachouh J. Polyetheretherketone (PEEK) for medical applications. J Mater Sci Mater Med [Internet]. 2016;27(7):118. Available from: https://doi.org/10.1007/s10856-016-5731-4
33. Krätzig T, Mende KC, Mohme M, Kniep H, Dreimann M, Stangenberg M, et al. Carbon fiber–reinforced PEEK versus titanium implants: an in vitro comparison of susceptibility artifacts in CT and MR imaging. Neurosurg Rev [Internet]. 2021;44(4):2163–70. Available from: https://doi.org/10.1007/s10143-020-01384-2
34. Yu W, Li X, Ma X, Xu X. Biomechanical analysis of inclined and cantilever design with different implant framework materials in mandibular complete-arch implant restorations. J Prosthet Dent [Internet]. 2022 May 1 [cited 2025 Jul 31];127(5):783.e1-783.e10. Available from: https://www.sciencedirect.com/science/article/pii/S0022391322001433?via%3Dihub
35. Müther M, Lüthge S, Gerwing M, Stummer W, Schwake M. Management of Spinal Dumbbell Tumors via a Minimally Invasive Posterolateral Approach and Carbon Fiber–Reinforced Polyether Ether Ketone Instrumentation: Technical Note and Surgical Case Series. World Neurosurg [Internet]. 2021 Jul 1 [cited 2025 Jul 31];151:277-283.e1. Available from: https://www.sciencedirect.com/science/article/pii/S1878875021006094?via%3Dihub
36. Guo Y, Chen C, Zhang S, Ren L, Zhao Y, Guo W. Mediation of mechanically adapted TiCu/TiCuN/CFR-PEEK implants in vascular regeneration to promote bone repair in vitro and in vivo. J Orthop Translat [Internet]. 2022 Mar 1 [cited 2025 Jul 31];33:107–19. Available from: https://www.sciencedirect.com/science/article/pii/S2214031X22000122?via%3Dihub
37. Yang Z, Guo W, Yang W, Song J, Hu W, Wang K. Polyetheretherketone biomaterials and their current progress, modification-based biomedical applications and future challenges. Mater Des [Internet]. 2025 Apr 1 [cited 2025 Jul 31];252:113716. Available from: https://www.sciencedirect.com/science/article/pii/S0264127525001364?via%3Dihub
38. Theivendran K, Arshad F, Hanif UK, Reito A, Griffin X, Foote CJ. Carbon fibre reinforced PEEK versus traditional metallic implants for orthopaedic trauma surgery: A systematic review. J Clin Orthop Trauma [Internet]. 2021 Dec 1 [cited 2025 Jul 31];23:101674. Available from: https://www.sciencedirect.com/science/article/pii/S0976566221005580?via%3Dihub

39. Laux CJ, Hodel SM, Farshad M, Müller DA. Carbon fibre/polyether ether ketone (CF/PEEK) implants in orthopaedic oncology. World J Surg Oncol [Internet]. 2018;16(1):241. Available from: https://doi.org/10.1186/s12957-018-1545-9

40. Perren SM. Current concepts of internal fixation of fractures. Manual of Internal Fixation. 1980;63–77.

41. Torstrick FB, Safranski DL, Burkus JK, Chappuis JL, Lee CSD, Guldberg RE, et al. Getting PEEK to Stick to Bone: The Development of Porous PEEK for Interbody Fusion Devices. Techniques in Orthopaedics [Internet]. 2017;32(3). Available from: https://journals.lww.com/techortho/fulltext/2017/09000/getting_peek_to_stick_to_bone__the_development_of.5.aspx

42. Chen Z, Chen Y, Wang Y, Deng J, Wang X, Wang Q, et al. Polyetheretherketone implants with hierarchical porous structure for boosted osseointegration. Biomater Res [Internet]. 2025 Jul 31;27(1):61. Available from: https://doi.org/10.1186/s40824-023-00407-5

43. Tarallo L, Mugnai R, Adani R, Zambianchi F, Catani F. A new volar plate made of carbon-fiber-reinforced polyetheretherketon for distal radius fracture: analysis of 40 cases. Journal of Orthopaedics and Traumatology [Internet]. 2014;15(4):277–83. Available from: https://doi.org/10.1007/s10195-014-0311-1

44. Hu X, Huang J, Wei Y, Zhao H, Lin S, Hu C, et al. Laser Direct-Write Sensors on Carbon-Fiber-Reinforced Poly-Ether–Ether–Ketone for Smart Orthopedic Implants. Advanced Science [Internet]. 2022 Apr 1;9(11):2105499. Available from: https://doi.org/10.1002/advs.202105499

**Table 1.** Parameters of the materials.

| **Material** | **Density (kg/m³)** | **Young's Modulus E (GPa)** | **Poisson's Ratio** |
|---|---|---|---|
| Cortical Bone | 1250 | 16.8 | 0.3 |
| Trabecular Bone | 120 | 0.15 | 0.2 |
| Titanium Alloy | 4540 | 110 | 0.34 |
| CF/PEEK Composite | 1444 | Horizontal: 3.6<br>Vertical: 18 | 0.3 |

**Table 2.** Contact definitions and interaction assumptions used in the finite element model

| Contact Interface | Contact Type | Description |
|---|---|---|
| Cortical bone - Cancellous bone | Bonded | — |
| Plate - Screw | Bonded | Simulates the structural connection of locking screws fixed within the plate, allowing minimal deformation while preventing separation. |
| Screw - Bone | Bonded | Replaces the original fully bonded assumption to represent potential differences in stress transfer at the screw-bone interface. |
| Fracture surface | Frictional (coefficient=0.3) | Simulates slight interfragmentary contact in the early postoperative stage, avoiding unrealistic complete fixation. |
| Plate - Bone | Non-contact (frictionless) | As the plate is positioned approximately 1 cm away from the cortical bone surface, |

| | | |
|---|---|---|
| | | frictionless contact was assumed. |

**Table 3.** Maximum Displacement (mm) in Each External Fixation Group Model and Incremental Increase Compared to the Control Group

| Loading Condition | Component | Titanium Alloy/Linear (Control, mm) | CF/PEEK/ Linear(mm) | CF/PEEK/ Non-linear(mm) | Linear CF/PEEK vs. Titanium Alloy ( % ) | Non-linear CF/PEEK vs. Titanium Alloy ( % ) |
|---|---|---|---|---|---|---|
| Longitudinal Load | Tibia | 3.660 | 4.015 | 4.025 | 9.70 | 9.97 |
| | Plate | 3.116 | 3.411 | 3.423 | 9.47 | 9.85 |
| | Screws | 3.120 | 3.398 | 3.407 | 8.91 | 9.20 |
| Longitudinal + Internal Rotation | Tibia | 3.956 | 4.385 | 4.394 | 10.84 | 11.07 |
| | Plate | 3.537 | 3.931 | 3.938 | 11.14 | 11.34 |
| | Screws | 3.495 | 3.881 | 3.881 | 11.04 | 11.04 |
| Longitudinal + External Rotation | Tibia | 4.004 | 4.491 | 4.491 | 12.16 | 12.16 |
| | Plate | 2.819 | 3.051 | 3.060 | 8.23 | 8.55 |
| | Screws | 3.591 | 4.012 | 4.019 | 11.72 | 11.92 |

**Table 4.** Maximum Stress (MPa) in Each External Fixation Group Model Compared to the Control Group

| Loading Condition | Component | Titanium Alloy/Linear (Control, MPa) | CF/PEEK/ Linear ( MPa ) | CF/PEEK/ Non-linear ( MPa ) | Linear CF/PEEK vs. Titanium Alloy ( % ) | Non-linear CF/PEEK vs. Titanium Alloy ( % ) |
|---|---|---|---|---|---|---|
| Longitudinal Load | Tibia | 53.121 | 53.585 | 53.141 | 0.87 | 0.04 |
| | Plate | 87.520 | 18.456 | 35.187 | -78.91 | -59.80 |
| | Screws | 74.609 | 57.954 | 54.238 | -22.32 | -27.30 |
| Longitudinal + Internal Rotation | Tibia | 52.350 | 52.547 | 52.098 | 0.38 | 0.48 |
| | Plate | 106.35 | 20.372 | 42.593 | -80.84 | -59.95 |
| | Screws | 87.045 | 64.094 | 55.792 | -26.37 | -35.90 |
| Longitudinal + External Rotation | Tibia | 57.890 | 54.833 | 54.400 | -5.28 | -6.03 |
| | Plate | 99.944 | 53.944 | 33.795 | -46.03 | -66.19 |
| | Screws | 84.030 | 55.204 | 61.780 | -34.30 | -26.48 |

**Tabel 5**. Maximum Displacement (mm) and Stress (MPa) in fracture site

| Loading Condition | Mechanical changes in Fracture ends | Titanium Alloy/Linear (Control) | CF/PEEK/ Linear | CF/PEEK/ Non-linear | Linear CF/PEEK vs. Titanium Alloy(%) | Non-linear CF/PEEK vs. Titanium Alloy(%) |
|---|---|---|---|---|---|---|
| Longitudinal Load | Displacement | 1.887 mm | 1.992 mm | 1.996 mm | 5.56 | 5.78 |
| | Stress | 17.047 MPa | 20.166 MPa | 20.171 MPa | 18.30 | 18.33 |
| | **Relative displacement** | 0.005 mm | 0.003 mm | 0.003 mm | / | / |
| Longitudinal + Internal Rotation | Displacement | 1.973 mm | 2.092 mm | 2.097 mm | 6.03 | 6.28 |
| | Stress | 17.966 MPa | 29.320 MPA | 28.972 MPa | 63.20 | 61.26 |
| | **Relative displacement** | 0.003 mm | 0.009 mm | 0.009 mm | / | / |
| Longitudinal + External Rotation | Displacement | 1.959 mm | 2.091 mm | 2.091 mm | 6.74 | 6.74 |
| | Stress | 34.873 MPa | 52.902 MPa | 51.828 MPa | 51.70 | 48.62 |
| | **Relative displacement** | 0.014 mm | 0.038 mm | 0.037 mm | / | / |

**Figure legends:**

**Figure 1:** The finite element model of two configurations for the distal screws.
Linear and non-linear arrangements of screws.

**Figure 2:** Displacement contour maps of each fracture model under longitudinal force loading: (A) Whole fracture model: Titanium alloy plate with linear screw arrangement; (B) Whole fracture model: CF/PEEK plate with linear screw arrangement; (C) Whole fracture model: CF/PEEK plate with non-linear screw arrangement; (D) Tibia model: In the group of titanium alloy plate with linear screw arrangement; (E) Tibia model: In the group of titanium CF/PEEK plate with linear screw arrangement; (F) Tibia model: In the group of titanium CF/PEEK plate with non-linear screw arrangement; (G) Plate model: In the group of titanium Titanium alloy plate with linear screw arrangement; (H) Plate model: In the group of titanium CF/PEEK plate with linear screw arrangement; (I) Plate model: In the group of titanium CF/PEEK plate with non-linear screw arrangement; (J) Screws model: In the group of titanium Titanium alloy plate with linear screw arrangement; (K) Screws model: In the group of titanium CF/PEEK plate with linear screw arrangement; (L) Screws model: In the group of titanium CF/PEEK plate with non-linear screw arrangement.

**Figure 3:** Displacement contour maps of each fracture model under combined longitudinal and internal or external rotational loading.
(A) Longitudinal and internal: Titanium alloy plate with linear screw arrangement; (B) Longitudinal and internal: CF/PEEK plate with linear screw arrangement; (C) Longitudinal and

internal: CF/PEEK plate with non-linear screw arrangement; (D) Longitudinal and external: Titanium alloy plate with linear screw arrangement; (E) Longitudinal and external: CF/PEEK plate with linear screw arrangement; (F) Longitudinal and external: CF/PEEK plate with non-linear screw arrangement.

**Figure 4:** Displacement contour maps at the fracture site for three different model under longitudinal loading and combined longitudinal with internal or external rotational loading.