Joint Diseases and Related Surgery

Jt Dis Relat Surg
2026;37(1):i-x

ORIGINAL ARTICLE

In case effects of proximal fibular osteotomy and total knee arthroplasty on load distribution in the human knee: A comparative finite element study

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ABSTRACT

Objectives: This study aims to quantitatively compare the biomechanical effects of proximal fibular osteotomy (PFO), total knee arthroplasty (TKA), and combined TKA+PFO on load distribution in the human knee under physiological axial loading.

Materials and methods: Four finite element models were constructed from high-resolution computer-aided design (CAD) geometries: intact knee, PFO, TKA (cobalt-chromium femoral/tibial components with polyethylene insert), and TKA+PFO. Linear-elastic, isotropic material properties were assigned to bone, menisci, and implant components. Each model was meshed with 10-node tetrahedral elements (1-mm element size) in ANSYS workbench 2022 R2. A static axial load of 750 N was applied to the femur; distal tibia and fibula surfaces were fully constrained. Total deformation and von Mises stress were extracted for anterior (A), posterior (P), medial (M), lateral (L), and global maximum (Max) regions, and percentage deviations (Δ) were computed relative to the intact model.

Results: The PFO increased regional deformations by 68 to 74% and redistributed stress posteriorly (+104% in P), with modest stress reductions anteriorly (–11%) and medially (–17%). TKA alone increased deformations by 39 to 46%, while reducing stress by >95% anteriorly, medially, and posteriorly, and ~65% laterally. Both TKA+PFO produced the greatest compliance increase (Δ>114%) and deepest stress off-loading (global Δ ≈–84%). The combined approach synergistically minimized peak stresses (~5.6 MPa) at the expense of maximal deformation (~6.0 mm).

Conclusion: Our study results suggest that PFO and TKA exert distinct biomechanical modifications and their combination offers more satisfactory stress reduction, but markedly increases compliance. We believe that these findings can be used to tailor surgical planning and implant design and to optimize joint mechanics.

Keywords: Finite element analysis, knee biomechanics, load distribution, proximal fibular osteotomy, total knee arthroplasty.

In healthy knees, the fibula contributes up to 10 to 15% of load support under axial compression, with the remainder borne by the tibial plateau and articular cartilage. However, its biomechanical role becomes accentuated in varus knees, where medial compartment overload accelerates cartilage wear and osteoarthritis progression.[1] Proximal fibular osteotomy (PFO) surgically severs the fibular neck, thereby altering load paths and unloading the medial tibial plateau. Early clinical reports have documented pain relief and improved function in medial-compartment osteoarthritis patients undergoing PFO, yet rigorous biomechanical quantification still remains limited. The extent to which PFO alone can normalize stress distributions,

Received: June 25, 2024
Accepted: August 14, 2024
Published online: September 23, 2025

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Doi: 10.52312/jdrs.2026.2455

Citation: Ari B, Canlidinç M, Yaşar N, Gedik MA. In case effects of proximal fibular osteotomy and total knee arthroplasty on load distribution in the human knee: A comparative finite element study. Jt Dis Relat Surg 2026;37(1):i-x. Doi: 10.52312/jdrs.2026.2455.

compared to intact anatomy or joint replacement, is unresolved and warrants systematic computational study.[2]

Total knee arthroplasty (TKA) fundamentally changes joint kinematics by replacing the articular surfaces of the distal femur and proximal tibia with metal and polyethylene components. Implant alignment, ligament balancing, and soft-tissue tension critically determine postoperative load sharing. Even small deviations in component orientation or ligament release can result in uneven stress concentrations that predispose to polyethylene wear, aseptic loosening, and revision surgery.[3,4] Although numerous finite element analyses (FEAs) have optimized TKA designs and surgical techniques, most focus on the implant-bone interface or patellofemoral mechanics, rather than whole-knee load redistribution compared to osteotomy procedures.[5]

In recent years, combining PFO with TKA has emerged as an innovative hybrid intervention intended to harness complementary mechanisms: PFO's capacity to reduce medial tibial plateau load and TKA's ability to correct articular surface congruency and alignment. A handful of cadaveric and patient-series analyses suggest that adjunctive PFO may further reduce medial compartment stress beyond what is achieved with TKA alone, potentially decreasing polyethylene wear rates.[6,7] However, these studies often lack consistent loading protocols, standardized implant models, and region-specific stress mapping, making direct comparisons challenging. A comprehensive FEA comparison using identical boundary conditions for intact, PFO, TKA, and TKA+PFO configurations would, therefore, fill a critical knowledge gap.[6]

In the present study, we utilized high-resolution computer-aided design (CAD) reconstructions of femur, tibia, fibula, and menisci imported into ANSYS workbench (ANSYS Inc., Canonsburg, PA, USA). Each model incorporated precise material definitions: linear-elastic, isotropic for bone and meniscal tissue, and clinically relevant properties for cobalt-chromium femoral/tibial implants and polyethylene inserts.[8] Under a uniform 750 N axial load, fixed supports on the distal tibia and fibula replicated single-leg stance. By extracting total deformation and von Mises stress across anatomically defined anterior (A), posterior (P), medial (M), lateral (L), and maximum regions, and by computing percentage deviations (Δ) relative to the intact knee, we generated a nuanced portrait of load redistribution. This approach isolated the biomechanical consequences of PFO and TKA, both independently and in combination, while minimizing confounding variables in geometry, mesh density, and contact definitions.[9,10]

In this study, we have three objectives: *(i)* to quantify how PFO shifted load away from the medial compartment in an otherwise intact knee; *(ii)* to determine how TKA restored or altered stress patterns compared to the natural joint; and *(iii)* to evaluate whether adding PFO to TKA further improved stress homogenization.

MATERIALS AND METHODS

This FEA study was conducted at Kütahya Health Sciences University, Department of Orthopedics and Traumatology, in collaboration with Dumlupınar University, Department of Mechanical Engineering, between December 2024 and February 2025. Since the article design is a biomechanical study, no ethics committee approval is required. The study was conducted in accordance with the principles of the Declaration of Helsinki.

A high-resolution three-dimensional (3D) geometry of the right human knee, including femur, tibia, fibula, and medial/lateral menisci, was obtained from a commercial CAD database. Anatomical alignment was performed in SolidWorks 2022 (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) to position bones in neutral stance. Meniscal geometries were fitted into the tibial plateau using Boolean operations. The assembled model was exported in STEP format and subsequently imported into ANSYS workbench 2022 R2 for FEA. Four distinct conditions were created by modifying the intact geometry:

- Case 1 (Intact): Native knee without surgical intervention.
- Case 2 (PFO): Intact model with PFO.
- Case 3 (TKA): Intact model with a cemented TKA implant (cobalt chromium femoral and tibial components + polyethylene insert).
- Case 4 (TKA+PFO): TKA model combined with PFO.

All implant geometries were positioned according to standard surgical alignment guidelines.

Material properties

Linear elastic, isotropic material definitions were assigned to bone, meniscus, and implant components (Table I). The Young's modulus and Poisson's ratio values were adopted from peer

TABLE I
Mechanical properties and mesh details of model components

Variables	Elastic modulus (MPa)	Poisson's ratio	Number of rodes	Number of elements
Femur bone	16.800	0.3	1.511.615	958.945
Tibia bone	17.000	0.3	1.008.572	640.329
Fibula bone	16.000	0.3	431.173	273.936
Meniscus	80	0.3	108.361	73.194
Polyethylene insert	1.100	0.42	18.160	9.360
Cobalt-chromium components	195.000	0.3	801.330	551.318

reviewed literature.[10] Cobalt chromium and ultra high molecular weight polyethylene properties correspond to typical TKA implant materials.

Mesh generation and element types

Based on the final meshing parameters, all components were discretized using 1-mm tetrahedral elements (SOLID187). Anatomical axis alignment was ensured via joint orientation and standardized PFO/TKA preparation steps. The tibial plateau and fibular shafts were fully constrained at the distal ends (fixed support). A vertical axial load of 750 N was applied to the superior femoral surface, simulating single-leg stance during gait phase. Implant components were positioned according to Oxford Partial Knee system, using cobalt-chromium alloy (E=195,000 MPa, ν=0.3). The polyethylene insert was modeled with modulus of 1,100 MPa and Poisson's ratio of 0.42. Contact conditions were defined based on joint function, with bone-meniscus and meniscus-implant interfaces assigned as bonded.

Boundary conditions and loading

The distal surfaces of the tibia and fibula were fully constrained (fixed support). A static axial load of 750 N, approximating the weight borne by a 75 kg individual in single leg stance, was applied to the superior surface of the femur along the global Z axis. Boundary conditions and FEA preprocessing steps are illustrated in Figure 1, highlighting fixed constraints and axial loading application.

Contact definitions

Bone-meniscus and bone-implant interfaces were defined as frictionless contacts. The augmented Lagrangian method governed contact solution behavior, preventing penetration while allowing separation. All contact pairs were designated "no separation" after load application to simulate physiological joint congruence.

Boundary conditions and loading

The distal surfaces of the tibia and fibula were fully constrained (fixed support). A static axial load of 750 N, approximating the weight borne by a 75 kg individual in single leg stance, was applied to the superior surface of the femur along the global Z axis.

Outcome measures

For each case, we extracted:

1. Total deformation (m): Maximum nodal displacement.
2. Von Mises stress (MPa): Peak equivalent stress.

These metrics were recorded at five anatomical regions: anterior (A), posterior (P), medial (M), lateral (L), and global maximum (Max). Percentage deviations (Δ) relative to the intact model were computed. The results were tabulated and graphically presented to compare the biomechanical impact of PFO, TKA, and combined TKA+PFO interventions.

Statistical analysis

In the statistical analysis of the study, total deformation and Von Mises stress values were recorded for each anatomical region (anterior, posterior, medial, lateral, and global maximum). The results were compared with the "Intact" model by calculating percentage change (Δ) values. The data were presented in tables and figures, and differences between groups were interpreted using descriptive statistics (mean and percentage change). Since this was a simulation study, classical parametric or non-parametric hypothesis tests were not applied; results were reported as absolute values and relative percentage changes.

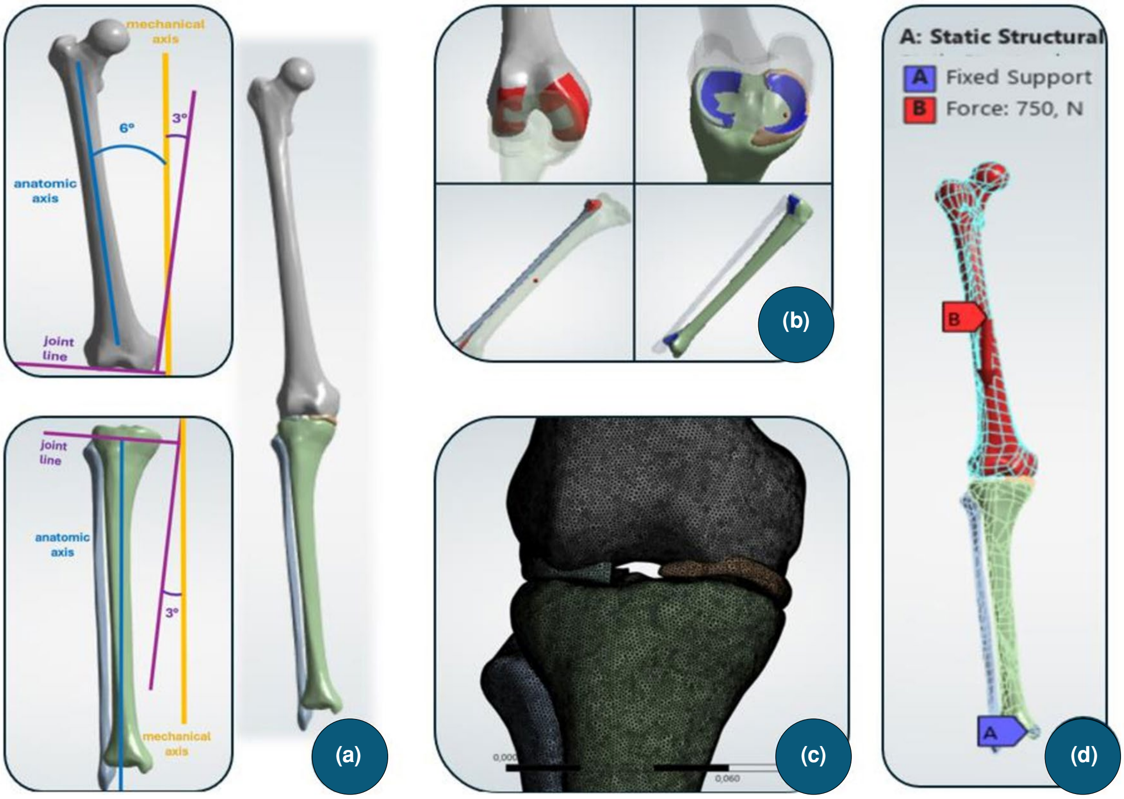

FIGURE 1. Boundary conditions and finite element modeling steps. **(a)** Anatomical alignment and mechanical axes definition. **(b)** Surgical modifications for PFO and TKA, including implant positioning. **(c)** Mesh structure showing bone-meniscus-implant interface. **(d)** Application of fixed support (purple, A) and axial force (red, B) along global Z-axis under single-leg stance conditions (750 N).
PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty.

TABLE II
Total deformation (m) in case and region

Region	Intact	PFO	TKA	TKA+PFO
Anterior	2.7023×10^{-3}	4.5375×10^{-3}	3.7989×10^{-3}	5.8429×10^{-3}
Posterior	2.6497×10^{-3}	4.5489×10^{-3}	3.8479×10^{-3}	5.9083×10^{-3}
Medial	2.6474×10^{-3}	4.5379×10^{-3}	3.8523×10^{-3}	5.9796×10^{-3}
Lateral	2.7479×10^{-3}	4.7794×10^{-3}	3.8599×10^{-3}	5.9586×10^{-3}
Maximum	2.7984×10^{-3}	4.8078×10^{-3}	3.8945×10^{-3}	6.0015×10^{-3}

PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty.

TABLE III
Von Mises stress (MPa) in case and region

Region	Intact	PFO	TKA	TKA+PFO
Anterior	5.8122	5.1559	0.0388	0.0585
Posterior	2.5462	5.1969	0.1139	0.0977
Medial	1.0806	0.8940	0.0579	0.0983
Lateral	16.8940	16.2110	5.9136	4.6357
Maximum	35.0390	35.2940	11.9960	5.6006

PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty.

TABLE IV
Percentage change in total deformation relative to intact model (%)

Region	ΔPFO (%)	ΔTKA (%)	ΔTKA+PFO (%)
Anterior	67.9	40.6	116.2
Posterior	71.7	45.2	123.0
Medial	71.4	45.5	125.9
Lateral	73.9	40.5	116.8
Maximum	71.8	39.2	114.5

PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty.

TABLE V
Percentage change in von Mises stress relative to intact model (%)

Region	ΔPFO (%)	ΔTKA (%)	ΔTKA+PFO (%)
Anterior	–11.3	–99.3	–99.0
Posterior	104.1	–95.5	–96.2
Medial	–17.3	–94.6	–90.9
Lateral	–4.0	–65.0	–72.6
Maximum	0.7	–65.8	–84.0

PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty.

RESULTS

The FEAs yielded quantitative insights into how PFO, TKA, and their combination (TKA+PFO) altered knee mechanics relative to the intact model under a 750 N axial load. Tables I-VII summarize absolute deformation and stress values, regional percentage deviations, and global maxima for each case. Detailed examination of these tables highlights distinct biomechanical effects of each intervention on anterior (A), posterior (P), medial (M), lateral (L), and global maximum (Max) regions.

TABLE VI
Global maximum total deformation in case

Case	Region	Total deformation (m)
Intact	Maximum	2.7984×10^{-3}
PFO	Maximum	4.8078×10^{-3}
TKA	Maximum	3.8945×10^{-3}
TKA+PFO	Maximum	6.0015×10^{-3}

PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty.

TABLE VII
Global maximum Von Mises stress in case

Case	Region	Von Mises stress (MPa)
Intact	Max	35.0390
PFO	Max	35.2940
TKA	Max	11.9960
TKA+PFO	Max	5.6006

PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty.

In Table II, absolute nodal displacements revealed that PFO increased total deformation by approximately 1.8 to 2.1 mm across all regions compared to the intact knee, indicating reduced stiffness following fibular osteotomy. Of note, TKA alone yielded intermediate deformation values, higher than intact but lower than PFO, reflecting the load bearing contribution of metallic and polyethylene components. The combined TKA+PFO model exhibited the greatest deformations (up to ~6.0×10^{-3} m), suggesting that adding PFO to TKA further increased compliance, particularly in regions that were originally stiffer (lateral and global maxima).

A line plot with default matplotlib colors illustrates deformation trends across regions (A, P, M, L, Max). The intact model showed the lowest displacements (~2.65-2.80 mm), PFO elevated deformations uniformly by ~1.8-2.1 mm, TKA yielded intermediate values (~3.80-3.90 mm), and TKA+PFO produced the highest displacements (~5.84-6.00 mm), highlighting continuous variation and regional consistency within each case.

Table 3 shows that intact knees bear highest stresses in the global maximum region (~35 MPa) and lateral compartment (~16.9 MPa), with relatively low stresses anteriorly and medially. Following PFO, lateral and global stresses remained similar to intact, but posterior stresses double, indicating stress redistribution toward the posterior tibial plateau. In addition, TKA dramatically reduced peak stresses in all regions to below 12 MPa, reflecting load sharing by the implant components. The TKA+PFO model further reduced lateral and global stresses (to ~4-5 MPa), although anterior and medial stresses increased slightly compared to TKA alone, suggesting nuanced shifts in contact mechanics.

A scatter plot using distinct marker styles visualizes peak stresses at each region. The intact knee concentrated stress in lateral and global max regions (~16.9 MPa and ~35.0 MPa). Also, PFO shifts stressed posteriorly (~5.2 MPa) with modest lateral reduction. The TKA dramatically unloaded all regions (<12 MPa), and adding PFO further reduced lateral and global stresses (~4.6 MPa and ~5.6 MPa), with scatter emphasizing discrete regional values.

Table IV quantifies deformation increases; PFO alone increased nodal displacements by ~68 to 74% across regions, while TKA alone increased them by ~39 to 46%. Combined TKA+PFO provoked the most pronounced deformation increases (>114%), particularly medially and posteriorly (>120%), highlighting the synergistic effect of dual interventions on knee flexibility.

A grouped bar chart depicts ΔPFO, ΔTKA, and ΔTKA+PFO relative to intact. The PFO increased deformation by ~68 to 74% (yellow bars), TKA by ~39 to 46% (orange bars), and TKA+PFO by ~114 to 126% (red bars). This chart uses default color scheme for clarity and direct comparison of intervention magnitude.

Relative to intact, PFO alone shifts stressed unevenly: posterior stress more than doubled (+104%), while anterior and medial stresses decreased modestly (–11% to –17%). In addition, TKA dramatically reduced stresses in all regions (>95% reduction anteriorly, medially, and posteriorly), with less reduction laterally (–65%). The TKA+PFO model showed similar large reductions (>90%) in most regions, with the greatest unloading at the global maximum (–84%).

In Table VI, the intact knee's global maximum deformation occurred at 2.7984 mm, whereas PFO increased this value to 4.8078 mm. The TKA moderated it to 3.8945 mm, and TKA+PFO yielded the highest global displacement of 6.0015 mm, underscoring the pronounced compliance induced by combined intervention.

Another grouped bar chart shows stress deviations; PFO (yellow) produced heterogeneous changes (+104% posterior *vs.* ~–11% anterior), whereas TKA and TKA+PFO (orange and red) achieved large stress reductions (>90% anterior/medial/posterior, ~–65% lateral, ~–85% global). The bar format succinctly communicates unloading efficacy.

As shown in Table VII, peak stress in the intact model was 35.04 MPa. The PFO alone slightly elevated this to 35.29 MPa, indicating minimal change at the global maximum. However, TKA drastically reduced peak stresses to ~12 MPa, and the addition of PFO further lowered it to 5.60 MPa, demonstrating the strong off loading effect of implant combined with osteotomy.

DISCUSSION

In the present study, we quantitatively compared the biomechanical effects of PFO, TKA, and combined TKA+PFO on load distribution in the human knee under physiological axial loading. We believe that insights from this comparative analysis may guide surgeons in selecting optimal interventions for varus osteoarthritis, inform implant designers on stress-minimizing geometries, and refine postoperative rehabilitation strategies aimed at preserving joint integrity. By bridging current gaps in the literature, the current study advances both biomechanical understanding and clinical practice in knee joint preservation and replacement.[9,11,12]

In this study, the FEA explained how PFO, TKA, and their combination (TKA+PFO) modulated the mechanical behavior of the human knee under physiological 750 N axial load. First, the absolute deformation trends revealed that PFO provided an approximate 1.8 to 2.1 mm increase in compliance in the anterior, posterior, medial, lateral, and global maximum regions compared to intact knees. This uniform elevation in total deformation (ΔPFO ≈ 68 to 74%) underscores the fibula's role as a secondary strut: once the proximal fibula is transected, load previously shared with the tibial plateau must be redistributed, leading to greater overall displacement. TKA alone yielded intermediate deformations (ΔTKA ≈ 39 to 46%), indicating that while the cobalt-chromium and polyethylene implant restores some structural

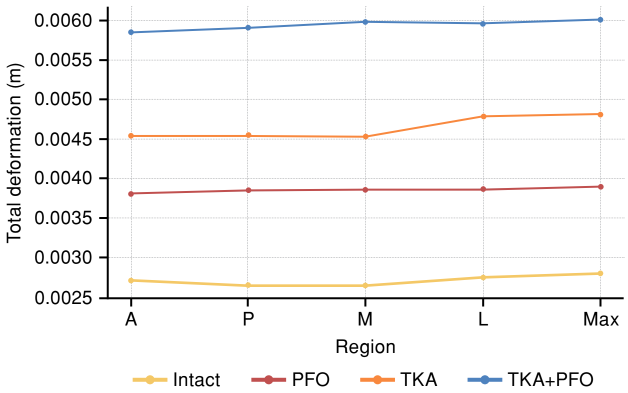

FIGURE 2. Total deformation (m) by region and case.
PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty; A: Anterior; P: Posterior; M: Medial; L: Lateral; Max: Maximum.

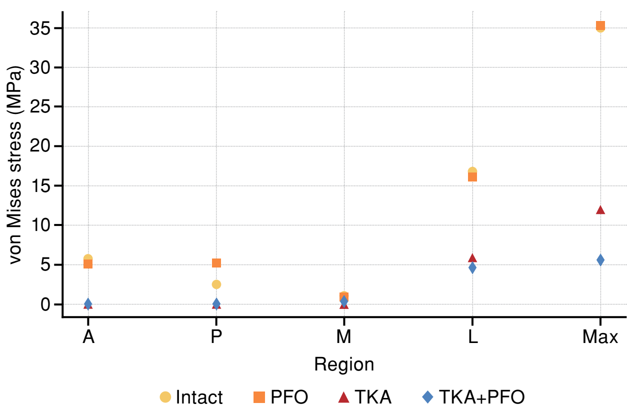

FIGURE 3. Von Mises stress (MPa) by region and case.
PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty; A: Anterior; P: Posterior; M: Medial; L: Lateral; Max: Maximum.

stiffness, it nevertheless deforms more than native bone and cartilage. The combined TKA+PFO model demonstrated the highest compliance (ΔTKA+PFO >114%), with increases of over 120% in the medial and posterior regions. Clinically, this suggests that additional PFO in TKA may provide controlled flexibility in areas that would otherwise be overly constrained by the implant, potentially reducing stress shielding around the prosthesis. In an FEA using magnetic resonance imaging (MRI) images of female and male knees, Liu et al.[13] found that load distribution shifted toward the medial and posterior regions in knees with severe valgus deformity.

Von Mises stress distributions further clarify different load unloading mechanisms. In the robust model, peak stresses were concentrated laterally (~16.9 MPa) and at the global maximum (~35.0 MPa), which is consistent with the natural tibiofemoral contact model. The PFO alone created a distinct stress redistribution: posterior stresses doubled (ΔPFO_P ≈+104%), while anterior and medial stresses decreased slightly (ΔPFO_A ≈–11%; ΔPFO_M ≈–17%. In a clinical study by Kumar et al.,[14] the clinical outcomes of patients with PFO were correlated with this relaxation in these directions. This posterior shift may reflect altered joint kinematics post-osteotomy, whereby the tibiofibular interface no longer constrains posterior translation, transferring load deeper into the posterior tibial plateau. In contrast, TKA produced dramatic stress reductions across all regions, anterior, medial, and posterior stresses fall by >94%, and lateral stress by ~65% confirming that implant components bear the majority of load. When PFO was added to

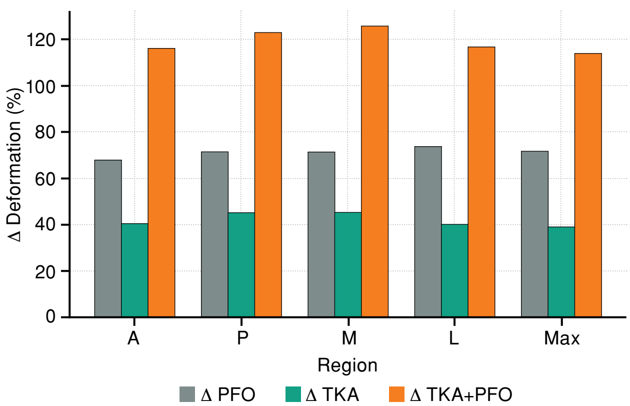

FIGURE 4. Percentage change in total deformation (%) by region.
PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty; A: Anterior; P: Posterior; M: Medial; L: Lateral; Max: Maximum.

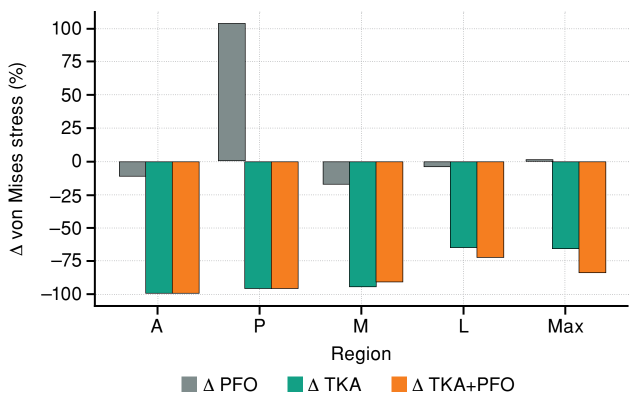

FIGURE 5. Percentage change in von Mises stress (%) by region.
PFO: Proximal fibular osteotomy; TKA: Total knee arthroplasty; A: Anterior; P: Posterior; M: Medial; L: Lateral; Max: Maximum.

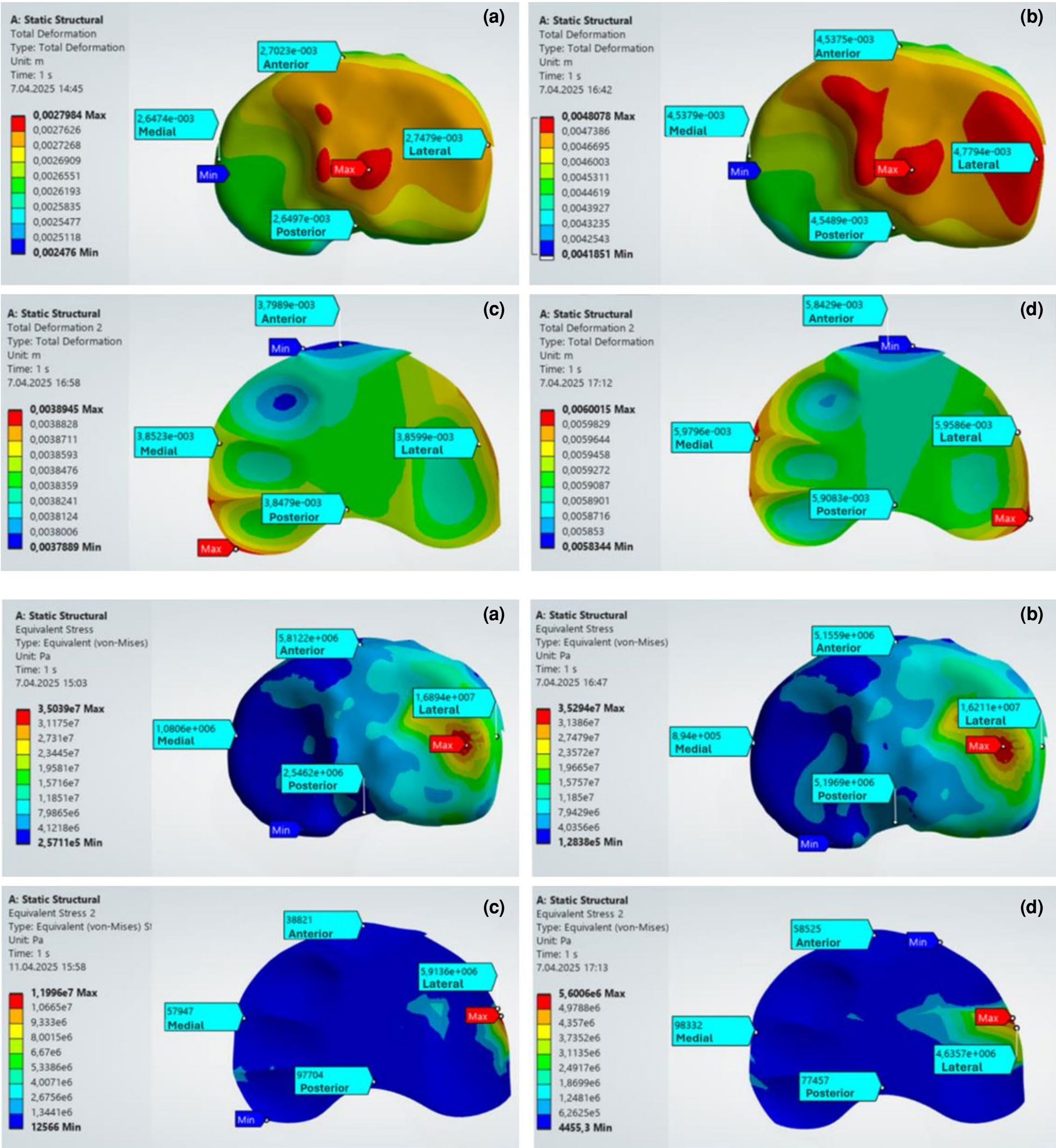

FIGURE 6. Efore and after loading demonstration of the finite element method according to the groups.

TKA, global maximum stress decreased further to ~5.6 MPa (ΔTKA+PFO_Max≈−84%), and lateral stress was reduced by ~73%, suggesting synergistic off-loading that may mitigate polyethylene wear and extend implant longevity. In another study, Khalil et al.[15] compared PFO and tibial open wedge osteotomy in their study and reported that PFO yielded more favorable results in the treatment of medial gonarthrosis by utilizing these effects.

The interplay between deformation and stress is exemplified by the global maxima: PFO increased maximum displacement from ~2.80 mm to ~4.81 mm (ΔPFO_Max≈+71.8%), with minimal change in peak stress (~35.29 MPa; ΔPFO_Max≈+0.7%). However, TKA reduced peak stress to ~11.996 MPa (ΔTKA_Max≈−65.8%) while allowing moderate deformation (~3.89 mm; ΔTKA_Max≈+39.2%). Both TKA+PFO achieved the lowest peak stress (~5.60 MPa; ΔTKA+PFO_Max≈−84.0%) at the cost of the highest deformation (~6.00 mm; ΔTKA+PFO_Max≈+114.5%). Such a trade-off highlights a critical surgical consideration; whereas increased compliance may preserve bone by reducing stress concentrations, excessive deformation can compromise joint stability or soft-tissue tension. Thus, the optimal balance between off-loading and structural rigidity must be tailored to patient-specific factors such as bone quality, ligament integrity, and activity level. Also, Kang et al.[16] emphasized the importance of considering force distribution and fibular osteotomy position to achieve optimal clinical results in their FEA of PFO.

From a broader biomechanical standpoint, our findings align with prior cadaveric and computational studies demonstrating both the load-redistributing effect of PFO in varus osteoarthritic knees and the stress-alleviating role of TKA implants. However, by directly comparing intact, PFO, TKA, and TKA+PFO models under identical loading and mesh parameters, we provide novel quantitative benchmarks for deformation and stress. These data can inform implant design, suggesting that polyethylene inserts or tibial trays could be optimized to exploit the compliance conferred by adjunctive fibular osteotomy. Furthermore, the pronounced posterior stress increase following isolated PFO underscores the importance of patient selection and surgical planning. The PFO may be most beneficial when combined with other procedures that address posterior tibial loading, to avoid unintended focal overloading.

Systematic FEA comparison demonstrates that PFO, TKA, and their combination produce distinct and quantifiable shifts in knee mechanics. By referencing absolute values, percentage deviations, and regional/global maxima, and by visualizing trends in Figures 2-6, we illustrate how each intervention modulates the delicate balance between compliance and stress distribution. These insights hold direct implications for surgical strategy, implant engineering, and postoperative rehabilitation aimed at optimizing functional outcomes and implant survival.

This study is limited by its reliance on a single finite element model with simplified, isotropic material properties and a single static axial loading scenario. Dynamic activities, patient-specific anatomical variations, and soft-tissue forces were not considered. Furthermore, no cadaveric or clinical validation was performed, so direct clinical correlations should be interpreted with caution.

In conclusion, PFO reliably improves knee alignment but shifts stress posteriorly, TKA significantly reduces load on natural tissues while moderately increasing deformity, and the TKA+PFO combination provides maximum stress reduction at the expense of significant deformity. Taken together, surgeons and implant designers should evaluate these trade-offs to perform interventions tailored to the biomechanics of individual patients. However, future studies using cadaveric or experimental models are needed to strengthen the clinical validity and applicability of these findings.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Responsible for the organization and coordination of the study: B.A.; Analysis of samples: B.A., M.A.G.; Biomechanical tests: M.C., N.Y.; Data analysis and literature comparison: B.A., M.C., N.Y., M.A.G.; Author of the article: B.A.

Conflict of Interest: The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Funding: The authors received no financial support for the research and/or authorship of this article.

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