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Research article

Finite Element Analysis of Tibial Stem Extensions in Total Knee Arthroplasty: Influence of Varus–Valgus Loading and Fatigue Resistance

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Abstract: Tibial stem extensions are widely adopted in revision total knee arthroplasty (TKA), yet their relevance in complex primary cases is not fully established. This finite element (FE) analysis compared tibial virtual constructs with and without a stem extension to assess stress distribution, deformation, and fatigue endurance. The model included the femoral component, tibia, tibial tray component, polyethylene insert, cement mantle, and optional stem, tested under compressive loading combined with varus and valgus angles of 3°, 5°, 7°, and 10°. In the standard configuration without a stem, peak stresses reached ~259 MPa under varus and ~300 MPa under valgus, while stem use consistently lowered stresses by roughly one quarter. Fatigue performance also improved, extending survival from about 360,000 cycles (equivalent to ~2 years) to more than 600,000 cycles (>3–4 years) with a stem. These results indicate that tibial stems help distribute loads more evenly, restrict micromotion, and enhance long-term durability. Clinically, such benefits may be most relevant in demanding primary TKA scenarios, including severe malalignment, bone loss, or compromised bone stock.

Keywords: total knee arthroplasty; tibial stem extension; finite element analysis; difficult primary; varus–valgus loading knee

1. Introduction

Total knee arthroplasty (TKA) is a highly successful intervention for severe osteoarthritis, yet component loosening remains one of the main mechanisms of failure and a frequent reason for revision. Micromotion at the bone–implant interface, malalignment, and compromised bone stock are recognized as contributors to early failure. [1–7]

Modular tibial stem extensions are designed to enhance primary stability and distribute loads more distally in the tibial canal. Their indications in complex primary TKA—such as severe varus–valgus deformities, large metaphyseal defects, or osteoporosis—remain under debate due to concerns about stress shielding, end-of-stem pain, and complexity of a potential revision. [8-13]

Finite element analysis (FEA) enables controlled, reproducible simulation of implant–bone mechanics in different loading scenarios that would be difficult to isolate in vivo. Prior work, including our 2022 study, has demonstrated that stem extensions can significantly lower peak stresses and displacements in degraded bone under compression, supporting their selective use in primary TKA when bone quality is poor. [1,3,8,14–15]

A new research interest comes up for us: (i) limited quantification of varus–valgus effects across multiple angles; (ii) incomplete comparison of stemmed versus stemless configurations under asymmetric loading; and (iii) sparse reporting of fatigue behavior beyond simple compression. [2,9,10,15]

The present study expands on those interests by combining multi-angle varus/valgus simulations with cyclic loading to emulate long-term use. We specifically evaluate stress distribution, deformation, and fatigue performance in stemless versus stemmed tibial constructs. [2–3,9,16]

We hypothesized that (1) tibial stems would reduce peak von Mises stresses and deformations at the tibial tray–bone interface under varus and valgus loads at neutral flexion, and (2) tibial stems would increase fatigue resistance under cyclic loading by redistributing stresses distally. [2,14–15]

2. Materials and Methods

2.1. Geometry Acquisition and Virtual Model Development

A specific 3D model of the proximal tibia was derived from CT data and validated against anatomical measurements. The femoral component, tibial tray, polyethylene insert, cement mantle, and modular tibial stem extension were modeled in Solidworks (Dassault Systèmes Solid-works Corp., Vélizy, France) and assembled into a virtual knee prosthesis construct for FE analysis. Bonded contacts were prescribed between components, and the distal tibia was constrained, consistent with prior work. [1,17]

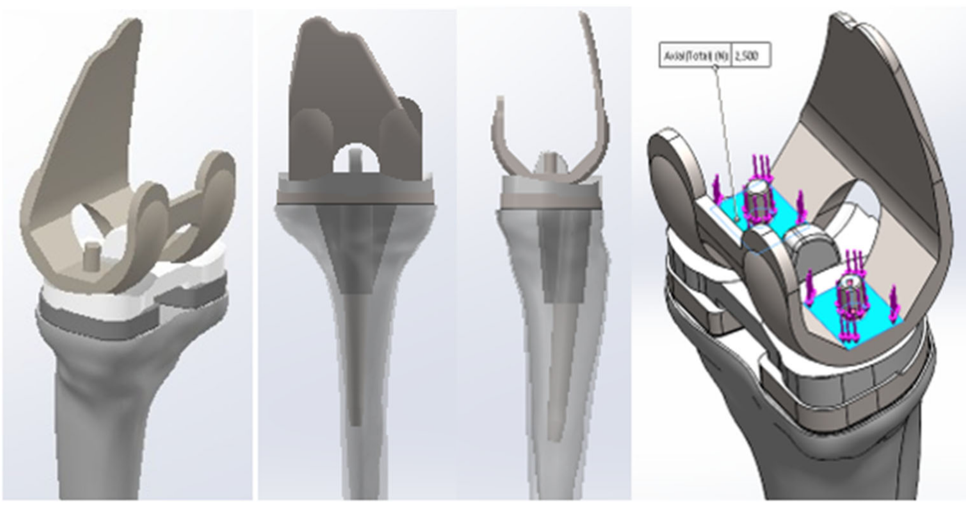

Figure 1. 3D assembly of components (femoral component, tibia, tray, insert, cement, stem).

2.2. Material Properties

Material properties were assigned as follows: cortical bone (E=18,000 MPa, ν=0.30), cancellous bone (E=700 MPa, ν=0.20), PMMA cement (E=2,150 MPa, ν=0.48), UHMWPE insert (E=1,070 MPa, ν=0.41), and CoCr components (E=104,800 MPa, ν=0.31). Values align with manufacturer specifications and other published studies. [8,18–20]

2.3. Meshing and Convergence

Each assembly was discretized using tetrahedral solid elements with local mesh refinement at the tibial tray–cement–bone interface and along the tibial canal in stemmed configurations. Mesh density was iteratively increased until successive refinements produced <5% change in peak von Mises stress. [17]

2.4. Boundary Conditions and Loading

Two configurations were simulated: (A) tibial tray without stem (stemless), and (B) tibial tray with modular stem extension (stemmed). Axial compression of 2500 N was applied across the tibial tray–insert interface at a neutral knee flexion position (standing). To evaluate the effect of coronal force malalignment, additional varus and valgus loading conditions were applied at 3°, 5°, 7°, and 10°. [2,15,21–22]

2.5. Contact Definitions and Constraints

All component interfaces were bonded to isolate the effect of global load transfer with and without stem extension. The distal tibial epiphysis was fixed to emulate diaphyseal support. [1]

2.6. Outcome Measures

Primary outcomes were: (i) peak von Mises stress in tibial bone and components; (ii) equivalent deformation (δech) of the tibial tray and stem; (iii) safety factor (FOS) maps; and (iv) cycles to fatigue initiation at representative tibial points. [4,14,23]

2.7. Fatigue Protocol

Cyclic compression was simulated to estimate the number of load cycles to fatigue at distal tibial locations, using walking-equivalent cycle counts. Reference calculations assume ~2000 cycles/day (~730,000 cycles/year) and assess behavior up to 10,000,000 cycles (~14 years). [14,23].

3. Results

3.1. Varus Loading (3°–10° varus loading force).

In the standard stemless configuration, varus loading produced concentrated stress peaks at the proximal tibial interface. Across varus loading angles (3°, 5°, 7°, 10°), peak von Mises stresses ranged on the order of ~253–259 MPa. With stem extension, peak stresses decreased across all varus angles (as seen in Table 1).

Table 1. Varus loading and stress reduction with stem.

Angle (°)	Stemless D.a Max σ_vM (MPa)	Stemmed D.b Max σ_vM (MPa)	% Reduction
3°	255.356	194.598	23.8%
5°	256.811	189.193	26.3%
7°	257.797	183.725	28.7%
10°	259.351	175.212	32.4%

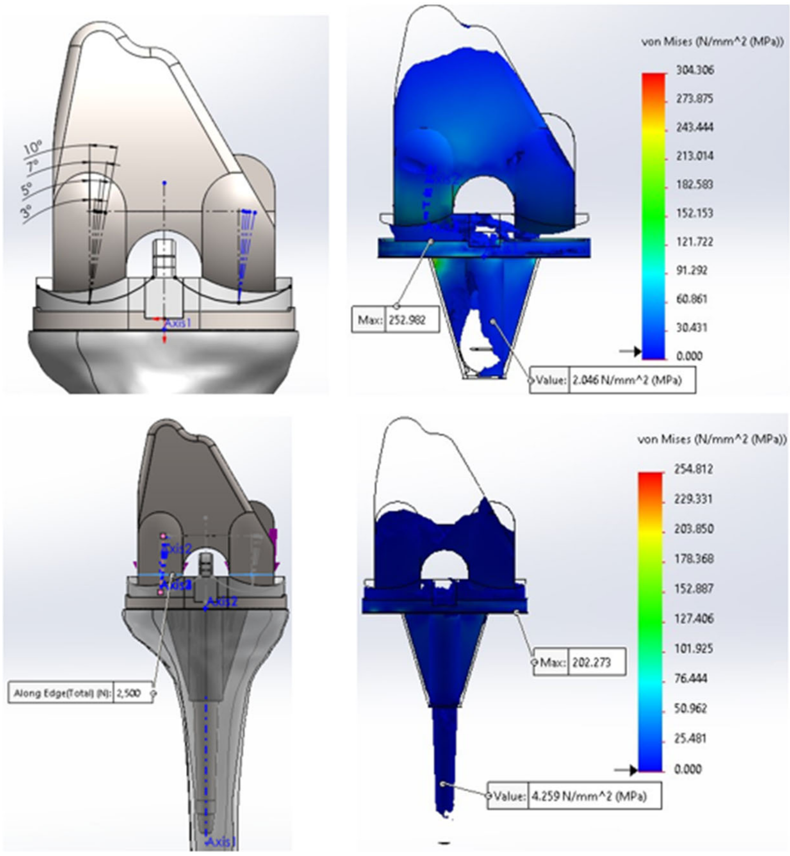

Figure 2. Varus: von Mises stress maps, stemless vs. stemmed.

3.2. Valgus Loading (3°–10° valgus loading force).

Valgus loading generated higher stresses than varus in the stemless model, with peaks reaching 300.405 MPa at 10°. With the stem extension, peak stresses decreased by approximately 25% at each angle (absolute reductions 71.3–76.5 MPa; see Table 2 for exact values).

Table 2. Valgus loading and stress reduction with stem.

Angle (°)	Stemless D.a Max σ_vM (MPa)	Stemmed D.b Max σ_vM (MPa)	% Reduction
3°	280.700	209.390	25.4%
5°	287.002	213.774	25.5%
7°	292.301	218.031	25.4%
10°	300.405	223.889	25.5%

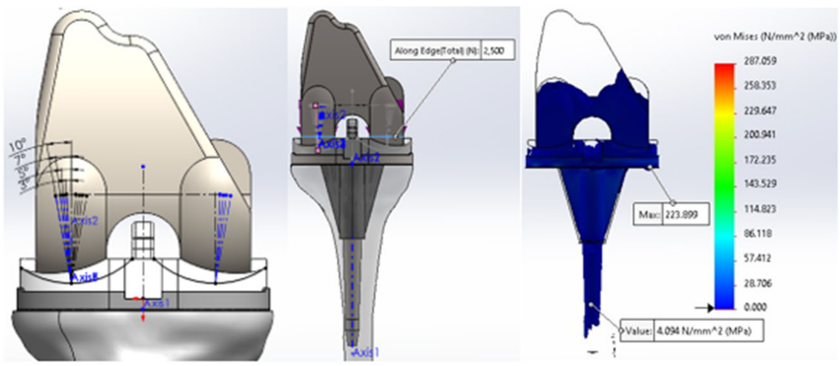

Figure 3. Valgus: von Mises stress maps.

3.3. Deformation

Maximum equivalent deformation (δech) occurred under varus in the stemless model (~0.95 mm), whereas the stemmed configuration limited deformation to <0.03 mm in varus and <0.01 mm in valgus.

3.4. Fatigue Resistance

Under cyclic compression, the stemless construct reached fatigue at approximately 360,000 cycles (~2 years of walking), while the stemmed construct exceeded 600,000 cycles (>3–4 years equivalent), indicating superior endurance under repetitive loads.

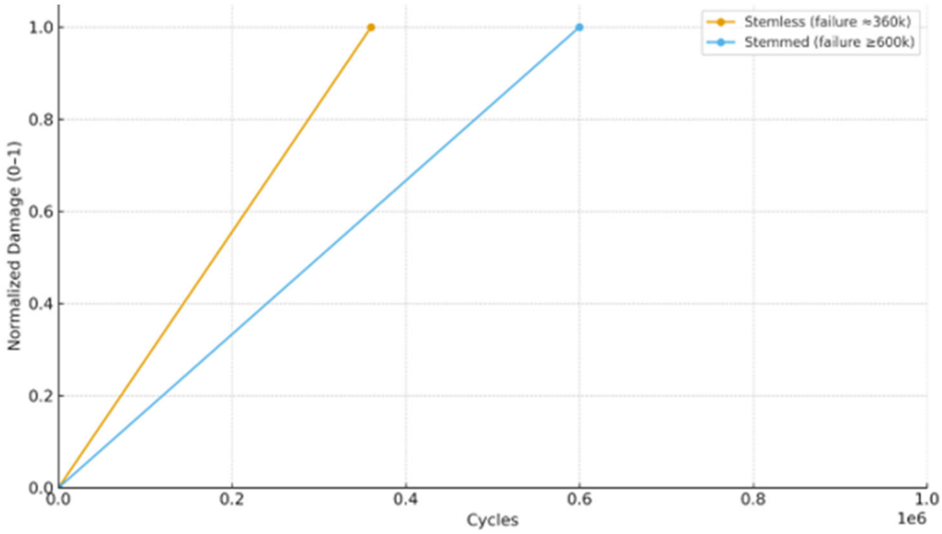

Figure 4. Fatigue curves (cycles to initiation/failure) for stemless vs. stemmed.

4. Discussion

We investigated the biomechanical impact of tibial stem extension in primary TKA across com-bined varus–valgus scenarios, complementing prior compression-focused studies. The principal findings are that stem extension (i) substantially reduces peak von Mises stresses at the proximal tibia, (ii) limits deformation of the tray–cement–bone construct, (iii) diminishes differences between varus and valgus responses, and (iv) improves fatigue resistance. [2,3,6,8,10,12]

Varus–valgus biomechanics: In stemless constructs, valgus loads produced higher peak stresses than varus at equivalent varus–valgus angles, consistent with clinical challenges in valgus knees. Adding a tibial stem redistributed load distally into the canal, effectively smoothing the discrepancy between varus and valgus and lowering absolute stresses across the tested angles (3°–10°). This equalization suggests that stems help buffer asymmetric coronal-plane moments that otherwise con-centrate proximally. [1,4,10,16]

Deformation and micromotion: The marked reduction of tray deformation from nearly 1 mm (varus) to a few hundredths of a millimeter with the stem implies a significant decrease in micromotion at the bone–cement interface. In the context of aseptic loosening risk, curbing interface motion below commonly cited thresholds is critical. [21]

Fatigue behavior: The doubling (or more) of cycles-to-fatigue in the stemmed configuration aligns with the notion that distal load sharing mitigates high-cycle stress accumulation at vulnerable proximal zones. Although clinical survivorship also depends on patient-related factors, these simulations reinforce the mechanical rationale for selecting stems in cases expected to experience higher cyclic loads (e.g., obesity, high activity, or severe deformities). [5,20,22]

Relation to literature: Our observations are in line with finite element and experimental evi-dence reporting reduced micromotion and improved stability with stems, and with engineering studies that focus on stem geometry (length/diameter) as determinants of stress transfer and shielding. Importantly, by explicitly comparing varus and valgus at different angles, our work adds quantitative context to when and how stems offer benefit. [2,6,8,23–25]

Limitations: A key methodological limitation of this study is the use of bonded contact definitions at all interfaces. While this approach isolates the effect of global load transfer with and without stem extension, it does not reproduce realistic micromotion at the cement–bone or tray–cement interfaces. As a result, absolute stress values and displacements may be underestimated. Future work should incorporate subject-specific ligamentous constraints, frictional interfaces with cement mantles, and adaptive bone responses to long-term load redistribution.. Prospective clinical correlation of valgus-dominant deformities with and without stems would further validate these findings. [26–29]

Clinical implications: For complex primary TKA with severe varus/valgus malalignment, osteo-porotic metaphyseal bone, or contained defects, tibial stems can be considered to enhance stability and reduce early mechanical failure risk. Choice of stem length and fixation method should be individualized to anatomy, defect size, and anticipated loading. [6,8,11,23]

5. Conclusions

Tibial stem extensions in primary TKA lower peak stresses, reduce deformation, and enhance fatigue resistance. By equalizing varus–valgus responses across the tested varus–valgus angles (3°–10°), stems provide a biomechanical margin of safety in complex primary knees with deformity or compromised bo-ne. These results support selective, indication-driven use of tibial stems to improve construct stability and longevity.

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