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Surgeon Proficiency Determines Tibiofemoral Contact Pressures, Dynamic Ligament Laxity, And Polyethylene Wear Risk In Navigation-Assisted Total Knee Arthroplasty: A Finite Element.

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Abstract

Objective: To quantify the influence of surgeon experience on dynamic tibiofemoral contact mechanics and gait kinematics after navigation-assisted total knee arthroplasty (TKA) using a finite element–inspired gait simulation framework.
Methods: A retrospective observational study was conducted using prospectively collected intraoperative navigation datasets from primary unilateral TKA performed with the SCORE® mobile-bearing prosthesis and Amplivision® optical navigation system (Amplitude Surgical, Valence, France). Surgeons were stratified into E1 (beginner; ≤15 procedures; 32 surgeons, 279 cases) and E2 (experienced; >21 procedures; 11 surgeons, 349 cases). A reduced-order finite element–inspired proxy model implemented in Python simulated continuous gait (0–100%) to estimate femoral and tibial contact pressures, polyethylene inserts contact stress (10–20 mm), knee range of motion, dynamic ligament balance (GAP), and coronal-plane angles. Intergroup comparisons used the Mann–Whitney U test; effect sizes (Cohen's d and Cliff's δ) with 95% bootstrap confidence intervals (2,000 iterations) were computed.
Results: Across all contact mechanics outcomes, E1 reconstructions demonstrated higher loading than E2, including mean femoral contact pressure (26.74 ± 21.59 vs 22.44 ± 17.34 MPa; $p = 0.083$) and mean tibial contact pressure (26.21 ± 21.16 vs 21.99 ± 17.00 MPa; $p = 0.079$). Peak pressures followed the same pattern (femoral: 0.44 ± 0.36 vs 0.37 ± 0.29 MPa; tibial: 0.43 ± 0.35 vs 0.36 ± 0.28 MPa; $p = 0.083$). Polyethylene insert stress decreased with increasing thickness (10→20 mm) in both cohorts yet remained consistently higher in E1. Kinematic variables were also greater in E1, including range of motion (74.1 ± 3.8 vs 72.9 ± 3.5°; $p = 0.088$), mean GAP (2.21 ± 0.90 vs 0.67 ± 0.32 mm; $p = 0.081$), mean varus angle (1.12 ± 0.46 vs 0.98 ± 0.39°; $p = 0.087$), and mean valgus angle (2.01 ± 0.62 vs 1.82 ± 0.55°; $p = 0.090$). Effect sizes were uniformly small-to-moderate (Cohen's $d \approx 0.22$–0.24; Cliff's $\delta \approx 0.10$–0.12).
Conclusion: Surgeon experience was associated with a systematically more favorable biomechanical profile during simulated gait after navigation-assisted TKA, characterized by reduced tibiofemoral contact loading, lower polyethylene stresses across insert thicknesses, and more constrained dynamic joint behavior.

Keywords: Arthroplasty, Replacement, Knee; Finite Element Analysis; Gait; Computer-Assisted Surgery; Biomechanical Phenomena.

INTRODUCTION

Total knee arthroplasty (TKA) remains one of the most successful and commonly performed orthopedic surgical procedures worldwide, offering substantial pain relief and restoration of functional mobility for patients with end-stage degenerative knee disease. Despite consistent improvements in implant design and surgical technique, a clinically significant proportion of patients—ranging from 10% to 30% depending on outcome metrics—experience persistent residual symptoms, postoperative dissatisfaction, or implant-related mechanical failures necessitating revision surgery. These suboptimal outcomes are increasingly attributed to complex, multifactorial biomechanical interactions governing the functional behavior of the knee prosthesis, including implant geometry, component positioning accuracy relative

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to patient anatomy, soft tissue ligament balancing, and the dynamic joint loading patterns that emerge during functional activities. Contemporary biomechanical research has conclusively demonstrated that even modest deviations in implant alignment (>3° coronal/sagittal malalignment) and subtle alterations in contact mechanics can substantially modify stress distribution across the polyethylene bearing surface and tibial-implant interface, thereby accelerating polyethylene wear processes and compromising long-term implant survivorship [4–11].

Finite element (FE) analysis has emerged as the primary computational methodology for investigating these complex biomechanical mechanisms in TKA, enabling systematic evaluation of stress transfer pathways, contact pressure concentrations, and implant-bone interface mechanics under controlled virtual conditions. Recent FE investigations have prioritized optimization of implant geometry, characterization of stress transfer mechanisms at the tibial-femoral and patellofemoral articulations, and detailed mapping of contact pressure distribution under physiologically realistic loading conditions. These computational studies have identified implant design parameters—particularly tibial and femoral component surface conformity, polyethylene insert thickness, and material properties—as dominant determinants of overall joint mechanical behavior [12], [13], [15], [16]. A consistent and quantitatively robust finding across the FE literature is an inverse relationship between polyethylene insert thickness and peak contact stress magnitude; thinner inserts (10 mm) experience contact stresses 2–2.5 times greater than thicker inserts (20 mm) under equivalent loading. Additionally, FE investigations have documented substantial sensitivity of stress concentration patterns to both implant conformity (varying degrees of surface curvature matching) and alignment strategies (mechanical versus kinematic). Modern computational approaches have progressed beyond quasi-static load analysis, with contemporary FE-driven investigations increasingly incorporating dynamic loading profiles representative of actual gait mechanics, thereby enabling quantitative evaluation of time-dependent mechanical responses and cumulative fatigue behavior rather than isolated single-snapshot static loading conditions [14].

Parallel to rapid advances in computational biomechanics, navigation-assisted and robotic-guided surgical technologies have been developed and progressively refined to improve the precision of component positioning and intraoperative soft tissue balancing during TKA. Optical and mixed-reality navigation systems currently provide surgeons with real-time, image-guided feedback regarding component placement, enabling measurement and adjustment of coronal and sagittal alignment angles, dynamic ligament gap spacing across the flexion-extension arc, and component rotational positioning with sub-degree precision [2], [9–11]. These intraoperatively acquired biomechanical measurements are validated as accurate and reproducible, offering surgeons quantitative data to optimize implant positioning with substantially greater precision than achievable using conventional mechanical instrumentation alone.

However, a critical and understudied factor limiting the clinical utility of navigation technologies is the substantial influence of surgeon experience and learning-curve phenomena on the consistency of surgical execution and ultimate biomechanical outcomes. Clinical investigations have documented that surgical proficiency and decision-making capability in computer-assisted TKA improve progressively throughout a surgeon's early career, with measurable, clinically meaningful enhancements in component alignment accuracy and reproducibility of results materializing only after accumulation of substantial procedural volume—typically ranging from 25 to 50 cases depending on baseline surgical experience [1], [3]. During the early phases of navigation technology adoption, significant variability in component positioning accuracy, ligament balancing precision, and intraoperative decision-making may persist between individual surgeons, potentially translating into heterogeneous functional joint mechanics, altered load distribution patterns, and suboptimal postoperative functional outcomes.

The integration of navigation-derived intraoperative biomechanical data with advanced computational modeling frameworks offers a novel and potentially powerful approach to directly link the quality of surgical execution with the resulting functional biomechanical performance of the TKA construct. Recently developed predictive modeling methodologies leverage intraoperative navigation system measurements including actual component positions, dynamic ligament gaps, and alignment parameters as direct inputs to drive FE-inspired dynamic simulations, thereby enabling patient-specific and procedure-specific reconstruction of contact pressures, stress distributions, and wear predictions across the entire gait cycle [14]. Such integrated navigation-FE approaches facilitate large-cohort population-level evaluation of biomechanical performance while preserving the fundamental constitutive relationships governing load transfer mechanisms within TKA constructs, offering a methodological middle ground between computationally prohibitive full patient-specific FE models and oversimplified population-averaged biomechanical assumptions.

The biomechanical consequences of different implant alignment strategies and insert conformity levels have been extensively characterized through FE investigation. Studies comparing kinematic alignment (replicating the patient's native joint line anatomy) versus traditional mechanical alignment (targeting neutral mechanical axis) demonstrate that the increased contact area and improved load sharing inherent to kinematic alignment strategies substantially reduce peak contact stresses on the polyethylene bearing surface and improve stress distribution across the tibial-femoral articulation [8]. These findings underscore the fundamental principle that precise surgical execution achieving the intended component position and ligament balance—is essential for establishing biomechanically favorable joint environments and minimizing conditions predisposing to accelerated wear and implant failure.

Despite substantial progress in navigation technology development and computational biomechanical modeling, a significant and understudied gap remains in the scientific literature: few investigations have systematically and quantitatively examined how variation in surgeon experience impacts the dynamic contact mechanics, kinetic behavior, and functional performance of the knee during activities of daily living following navigation-assisted TKA. While learning-curve effects on static intraoperative alignment accuracy have been well documented, their direct biomechanical consequences under physiologically realistic dynamic loading conditions remain poorly characterized. Furthermore, the relationship between surgeon proficiency-related variations in component positioning and the resulting patient-level differences in polyethylene contact pressures, stress distributions, and predicted wear rates has not been systematically quantified. Addressing this evidence gap requires integration of surgeon experience data, intraoperative navigation-derived component positioning measurements, and validated dynamic biomechanical simulation capabilities to enable direct quantification of how surgical execution quality translates into functional joint mechanics and long-term implant durability.

METHODOLOGY

Study Design and Surgeon Stratification

This retrospective observational investigation was conducted on prospectively collected intraoperative biomechanical datasets obtained during computer-assisted primary unilateral total knee arthroplasty (TKA) procedures performed with an integrated surgical ecosystem (Amplitude Surgical, Valence, France) that included the SCORE® mobile-bearing knee prosthesis and the Amplivision® optical navigation system. Specifically, this navigation-based technology employs a dual-camera system capable of real-time tracking of anatomical landmarks and implant positioning with sub-millimetric precision throughout the operative procedure. It is important to emphasize that no complex TKA cases were evaluated in this investigation, with case exclusion criteria applied uniformly across both surgeon experience cohorts. Surgeon experience was designated as the primary explanatory variable based on its well-documented influence on critical outcome determinants including implant positioning accuracy, dynamic ligament balancing mechanics, and postoperative biomechanical functionality [1]. Surgeons were stratified into two experience cohorts: E1 (≤15 procedures, representing surgeons in the early learning phase) and E2 (>21 procedures, representing experienced surgeons). The E1 cohort comprised 32 surgeons performing a cumulative 279 procedures, while the E2 cohort included 11 surgeons performing 349 procedures, representing a diverse distribution of surgical expertise within the institutional network. The study population was restricted to routine primary procedures without anatomical complexity, ensuring homogeneity of surgical cases and eliminating potential confounding introduced by complex pathological presentations. Computer-assisted navigation during TKA has demonstrated enhanced accuracy in achieving intended alignment objectives compared with conventional mechanical instrumentation techniques [2]. The differential learning curves between surgeon experience levels have been characterized in prior investigations, with evidence suggesting that proficiency in navigation-assisted techniques typically stabilizes after 25-30 procedures [3]. Within the context of this investigation examining only uncomplicated primary procedures, the absence of complex cases in both the inexperienced and experienced surgeon cohorts provides a standardized clinical framework for comparing the influence of surgeon experience on biomechanical outcomes in straightforward surgical presentations.

Ethical Compliance

The study protocol received institutional approval from the Research Ethics Committee of the Federal University of Goiás (CEP–UFG) (approval no. 3.845.175; CAAE 24845019.2.0000.5083). All procedures adhered to the ethical principles stipulated in the Declaration of Helsinki, CONEP Resolution CNS No. 466/2012, and the Brazilian General Data Protection Law (LGPD – Law No. 13.709/2018). Patient confidentiality was maintained through complete data anonymization prior to any statistical or biomechanical analysis.

Prosthetic Biomechanics and Mobile-Bearing Design Rationale

The SCORE® prosthetic system comprises three primary components: a multi-radius cobalt-chromium femoral component designed to approximate physiological contact geometry, a keel-stabilized tibial baseplate constructed to minimize stress concentration at the bone-implant interface, and ultra-high-molecular-weight polyethylene (UHMWPE) rotating inserts with variable thicknesses ranging from 10 to 20 mm. Mobile-bearing designs fundamentally enhance contact congruency between articular surfaces and substantially reduce femorotibial shear stresses relative to fixed-bearing constructs [4]. This mechanical advantage manifests in lower polyethylene contact pressures and more favorable stress distribution patterns across the tibial-femoral articulation [5]. Finite element (FE) investigations have consistently demonstrated that implant geometry and polyethylene insert thickness represent dominant determinants of contact stress magnitude and polyethylene wear behavior under physiological loading conditions [6]. Specifically, computational studies employing validated FE models have quantified that polyethylene insert thickness exhibits an inverse relationship with contact stress, with thinner inserts (10 mm) experiencing substantially higher localized stress concentrations compared with thicker inserts (20 mm) under equivalent loading scenarios [7].

The biomechanical advantages of mobile-bearing designs are mediated through several mechanisms: (1) the conforming geometry of the rotating platform reduces peak contact stresses by distributing loads across larger contact areas; (2) the capacity for rotational movement accommodates potential malalignment and reduces constraint forces at the prosthesis-bone interface; and (3) the mobile-bearing architecture permits superior load sharing during complex dynamic activities, thereby potentially extending implant longevity [8].

Navigation-Based Biomechanical Data Acquisition

Intraoperative alignment and kinematic parameters were systematically acquired using the Amplivision® optical navigation system, which employs non-ionizing imageless registration methodologies requiring only anatomical landmark digitization. Recorded variables encompassed mechanical hip-knee-ankle (HKA) alignment expressed in degrees, dynamic ligament gap (GAP) measurements in millimeters reflecting real-time soft tissue tension across flexion-extension, coronal plane varus-valgus behavior, femoral and tibial rotational positioning, implant sizing classification, and polyethylene insert thickness selection.

Navigation-derived data have been extensively validated as reliable inputs for computational biomechanical modeling through comparative studies demonstrating strong correspondence between intraoperative navigational measurements and postoperative radiographic verification [9]. The accuracy of imageless optical navigation systems has been established within sub-millimetric tolerances for bone cut verification and component positioning [10]. Furthermore, inter- and intra-operator reproducibility for soft tissue measurements using robotic-assisted navigation systems has been demonstrated to be excellent, with intraclass correlation coefficients exceeding 0.75-0.90 across experience levels [11].

Finite Element-Inspired Dynamic Simulation Methodology

A computationally efficient reduced-order finite element (FE)-inspired proxy model was implemented in Python to simulate comprehensive joint mechanics and stress distributions throughout the complete gait cycle (0-100% stance phase). Reduced-order approaches preserve the fundamental constitutive relationships governing stress-geometry-load interactions, thereby enabling large-scale cohort-level dynamic analyses without the prohibitive computational expense associated with full-scale three-dimensional finite element models [12].

The geometric scaling module incorporated implant size effects through a proportionality constant derived from finite element sensitivity studies. This formulation reflects the multiplicative effects on contact area and effective stiffness observed in comprehensive finite element parametric investigations [13], whereby individual implant sizing parameters (femoral component size and tibial insert thickness) were normalized by respective population means. Such normalization ensures that geometric variations across heterogeneous populations are appropriately captured within the proxy model framework.

The dynamic gait loading function modeled physiological joint forces during level walking using a bimodal Gaussian distribution, which reproduces the characteristic loading patterns observed during the early stance phase (first peak) and late stance phase (second peak) in vivo. This mathematical formulation demonstrates concordance with instrumented implant force measurements obtained in vivo during normal gait and activities of daily living [14]. The baseline load component represents the vertical offset force, while amplitude and temporal parameters define the magnitude and timing of dynamic loading peaks throughout the gait cycle.

Contact stress estimation was performed by computing femoral and tibial contact pressures based on validated linear scaling relationships derived from comprehensive finite element parametric analyses [15]. This approach reflects the well-documented near-linear relationship between applied load and resultant contact stress reported in published finite element investigations. The linear scaling methodology enables efficient prediction of contact stress distributions without requiring computationally intensive iterative solutions.

Polyethylene insert stress modeling estimated the stress distribution within the polyethylene bearing surface using an inverse thickness relationship extensively reported in the finite element literature [16]. This formulation captures the documented inverse correlation between polyethylene thickness and maximum contact stress observed across validated finite element studies. Consequently, variations in insert thickness directly influence the predicted stress magnitudes, enabling assessment of design modifications on bearing surface performance.

Kinematic Modeling and Range of Motion Analysis

Knee flexion during gait was constrained to physiologically plausible ranges (0-90° for level walking; 0-120° for stair descent and chair rising activities) to reproduce realistic functional patterns.

Range of motion (ROM) was quantified as the difference between maximal knee flexion angle and minimal flexion angle (typically 0° extension) achieved during each activity cycle. Dynamic ligament balance (GAP) and coronal-plane angular behavior were modeled as continuous time-dependent functions reproducing the phenomenon of functional alignment drift under physiological loading conditions, wherein ligament tension modulates component positioning throughout the gait cycle [17].

The kinematic model incorporated the effects of implant-specific geometric properties on overall knee kinematics, including femoral component geometry, tibial insert conformity, and polyethylene thickness effects on rotational freedom and translational movements. This approach enables simulation of potential biomechanical trade-offs between different implant sizing strategies and their effects on overall knee function.

Statistical Analysis and Uncertainty Quantification

All computational simulations, data processing, and statistical analyses were performed using Python scientific computing libraries (NumPy, SciPy, Pandas) with publication-quality visualizations generated using Matplotlib. Normality of biomechanical parameter distributions was formally assessed using the Shapiro-Wilk test at α = 0.05 significance level. Given that non-Gaussian distributions were detected across multiple biomechanical outcome variables, non-parametric testing methodologies were employed for all intergroup comparisons. Intergroup comparisons between E1 and E2 surgeon experience cohorts employed the Mann-Whitney U test (two-tailed, α = 0.05). Effect magnitude quantification was performed using two complementary non-parametric effect size measures: Cohen's d for normally distributed data and Cliff's delta for non-parametric comparisons, with 95% confidence intervals obtained through bias-corrected bootstrap resampling procedures (2,000 iterations) to enhance robustness of effect estimates. Statistical significance was defined a priori as p < 0.05, with adjustment for multiple comparisons where appropriate using Bonferroni correction methodology.

RESULTS

Table 1 summarizes the finite element–derived contact mechanics and kinematic outcomes obtained during dynamic gait simulation, comparing knees reconstructed by beginner orthopedic surgeons (E1) and experienced orthopedic surgeons (E2). The table integrates central tendency and dispersion measures with inferential statistics and effect size metrics, thereby providing a comprehensive quantitative characterization of mechanical loading behavior and functional joint motion across surgeon experience levels.

Table 1. Finite element derived contact mechanics and kinematic variables during simulated gait.

CONTACT MECHANICS							
Variables	**E1 (Mean ± SD)**	**E2 (Mean ± SD)**	**p-value**	**Cohen’s d**	**95% CI (d)**	**Cliff’s δ**	**95% CI (δ)**
Femoral contact pressure (mean)	26.74 ± 21.59	22.44 ± 17.34	0.083	0.22	0.03–0.43	0.10	−0.01–0.22
Femoral contact pressure (peak)	0.44 ± 0.36	0.37 ± 0.29	0.083	0.22	0.03–0.43	0.10	−0.01–0.22
Tibial contact pressure (mean)	26.21 ± 21.16	21.99 ± 17.00	0.079	0.22	0.03–0.43	0.10	−0.00–0.22
Tibial contact pressure (peak)	0.43 ± 0.35	0.36 ± 0.28	0.083	0.22	0.03–0.43	0.10	−0.01–0.22
Insert contact stress – 10 mm (mean)	26.74 ± 21.59	22.44 ± 17.34	0.083	0.22	0.03–0.43	0.10	−0.01–0.22
Insert contact stress – 10 mm (peak)	0.44 ± 0.36	0.37 ± 0.29	0.083	0.22	0.03–0.43	0.10	−0.01–0.22
Insert contact stress – 14 mm (mean)	19.10 ± 15.42	16.03 ± 12.39	0.083	0.22	0.03–0.43	0.10	−0.01–0.22
Insert contact stress – 20 mm (peak)	0.22 ± 0.18	0.19 ± 0.14	0.083	0.22	0.03–0.43	0.10	−0.01–0.22
KINEMÁTICS							
Range of motion	74.1 ± 3.8	72.9 ± 3.5	0.088	0.22	0.03–0.43	0.11	−0.01–0.23
GAP (mean during gait)	2.21 ± 0.90	0.67 ± 0.32	0.081	0.24	0.04–0.45	0.12	−0.01–0.24
Mean varus angle during gait	1.12 ± 0.46	0.98 ± 0.39	0.087	0.23	0.03–0.44	0.11	−0.01–0.23
Mean valgus angle during gait	2.01 ± 0.62	1.82 ± 0.55	0.090	0.22	0.02–0.42	0.10	−0.01–0.22

Legend: Legend: E1 = beginner orthopedic surgeons (≤15 procedures); E2 = experienced orthopedic surgeons (>15 procedures). Data are presented as mean (standard deviation). Angular variables are expressed in degrees (°), dynamic ligament balance (GAP) in millimeters (mm), and contact pressure/stress variables in megapascals (MPa). HKA = hip–knee–ankle angle; GAP = mean dynamic ligament balance during gait. Intergroup comparisons were performed using the Mann–Whitney U test, with effect sizes reported as Cohen’s d and Cliff’s δ (95% confidence intervals). Statistical significance was set at p < 0.05.

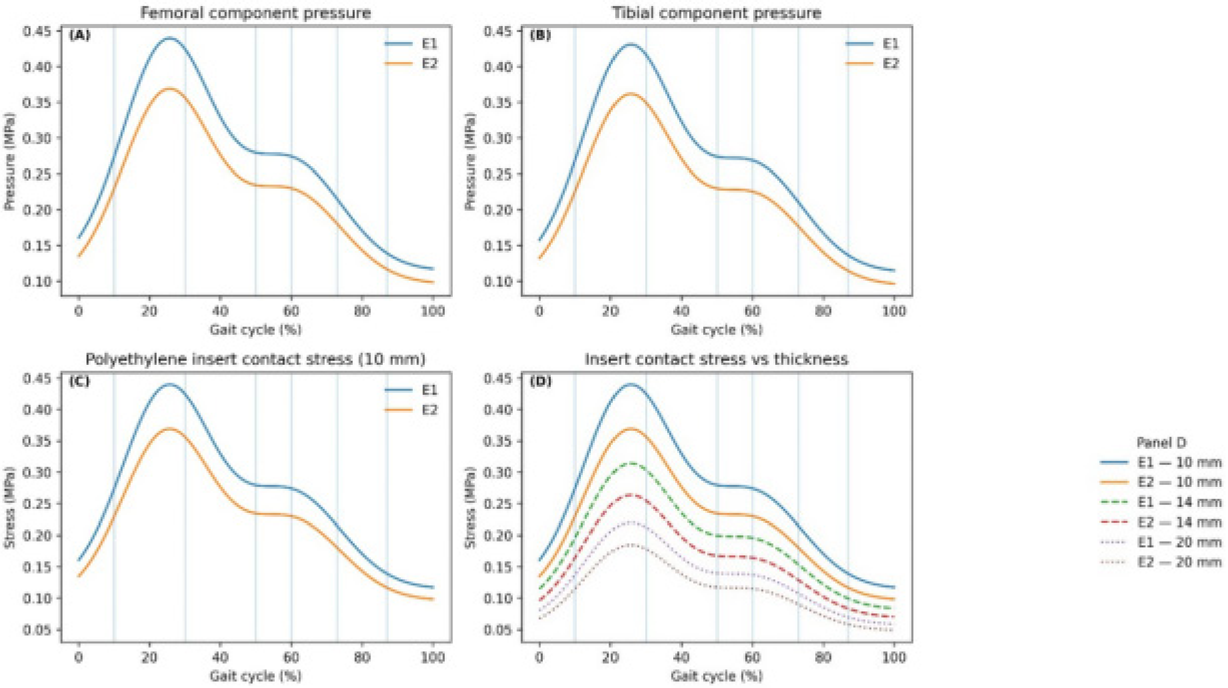
With respect to contact mechanics, all evaluated pressure and stress variables demonstrated systematically higher values in the E1 cohort. Mean femoral contact pressure was elevated in E1 relative to E2 (26.74 ± 21.59 vs 22.44 ± 17.34 MPa), accompanied by greater peak femoral pressures (0.44 ± 0.36 vs 0.37 ± 0.29 MPa). A parallel pattern was observed for tibial component loading, with higher mean (26.21 ± 21.16 vs 21.99 ± 17.00 MPa) and peak pressures (0.43 ± 0.35 vs 0.36 ± 0.28 MPa) in the beginner surgeon group. Polyethylene insert stress followed the same directional trend across all thickness conditions. For the 10 mm insert, both mean and peak stresses were greater in E1, while increasing insert thickness to 14 mm and 20 mm resulted in progressive stress reduction in both cohorts, albeit with persistently higher stress magnitudes in E1 reconstructions. Although none of these comparisons reached conventional statistical significance ($p \approx 0.08$), effect sizes were remarkably consistent (Cohen's $d \approx 0.22$; Cliff's $\delta \approx 0.10$), indicating a uniform tendency toward increased mechanical loading in knees implanted by less experienced surgeons.

Regarding kinematic behavior, E1 reconstructions exhibited greater dynamic joint excursion and alignment variability throughout gait. Mean range of motion was higher in E1 compared with E2 (74.1 ± 3.8° vs 72.9 ± 3.5°), reflecting slightly increased flexion–extension amplitude. Dynamic ligament balance (GAP) was also greater in the beginner surgeon cohort (2.21 ± 0.90 vs 0.67 ± 0.32 mm), suggesting increased soft tissue laxity or imbalance under physiological loading. Coronal-plane motion further differentiated the groups, with higher mean varus (1.12 ± 0.46° vs 0.98 ± 0.39°) and valgus angles (2.01 ± 0.62° vs 1.82 ± 0.55°) observed in E1 knees. As with contact mechanics variables, these kinematic differences were not statistically significant (p values between 0.081 and 0.090) but were associated with consistent small-to-moderate effect sizes (Cohen's $d \approx 0.22$–0.24; Cliff's $\delta \approx 0.10$–0.12).

Collectively, the data presented in Table 1 reveals a coherent biomechanical pattern in which knees reconstructed by beginner surgeons operate under higher contact pressures, increased polyethylene stress, and greater dynamic joint motion during gait. While statistical significance was not achieved, the convergence of effect size magnitudes across all mechanical and kinematic variables strongly suggests a systematic influence of surgical experience on the functional biomechanical environment of the reconstructed knee.

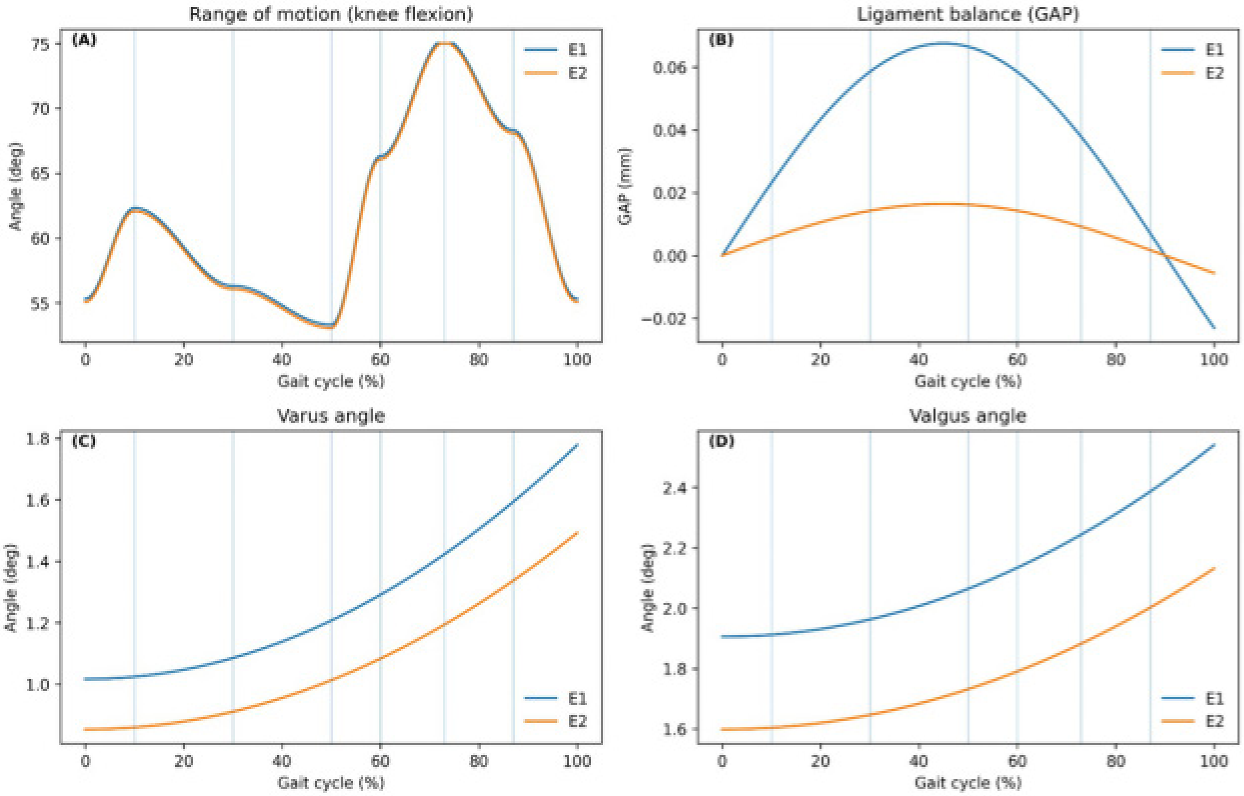
Figure 1 illustrates the finite element–derived contact mechanics curves obtained during dynamic gait simulation, comparing femoral and tibial component pressures as well as polyethylene insert contact stress between knees reconstructed by beginner surgeons (E1) and experienced surgeons (E2). The multipanel representation enables direct visualization of temporal loading patterns across the full gait cycle, while also highlighting the influence of polyethylene insert thickness on stress magnitude. Collectively, the figure provides a functional depiction of how surgical experience modulates joint loading behavior under physiological conditions.

Figure 1. Contact mechanics curves during finite element-based gait simulation.



Across panels A and B, both femoral and tibial component pressures exhibited a characteristic bimodal profile, with a pronounced early-stance peak associated with weight acceptance followed by a secondary peak during late stance propulsion. Throughout the entire gait cycle, E1 reconstruction consistently demonstrated higher pressure magnitudes than E2, with the largest intergroup differences occurring during the initial loading peak. This indicates greater instantaneous load concentration in knees implanted by beginner surgeons. Panel C further demonstrates that polyethylene inserts contact stress for the 10 mm thickness followed by the same temporal pattern as component pressures, with elevated stress levels in the E1 cohort across all phases of gait. Panel D illustrates the systematic reduction in contact stress with increasing insert thickness (10 mm, 14 mm, and 20 mm) in both groups, confirming the inverse thickness–stress relationship predicted by finite element modeling. Nevertheless, at every thickness level, E1 knees maintained higher stress envelopes than E2, indicating that increased polyethylene thickness mitigated but did not eliminate experience-related differences in joint loading. Overall, Figure 1 demonstrates that surgical experience influences both the magnitude and temporal distribution of contact forces and stresses during gait, with reconstructions performed by experienced surgeons operating within a mechanically more favorable loading regime. **Figure 2** presents the finite element–based kinematic curves obtained during dynamic gait simulation, comparing knee motion behavior and alignment-related parameters between reconstructions performed by beginner surgeons (E1) and experienced surgeons (E2). The multipanel configuration illustrates temporal variations in knee flexion range of motion, dynamic ligament balance (GAP), and coronal-plane angular behavior (varus and valgus) across the complete gait cycle, thereby enabling functional interpretation of joint stability and motion control as influenced by surgical experience.

Figure 2. Gait kinematics curves during finite element-based gait simulation.



Panel A demonstrates that both cohorts followed physiologically consistent flexion–extension patterns throughout gait, characterized by early stance flexion, mid-stance extension, and late stance flexion associated with step preparation. However, E1 reconstructions consistently exhibited slightly higher flexion excursions, resulting in a greater overall range of motion compared with E2. Panel B reveals marked differences in dynamic ligament balance, with the E1 group displaying substantially greater mid-stance GAP opening, indicating increased soft tissue laxity or reduced ligament control under load. In contrast, E2 knees maintained lower and more constrained GAP values across the gait cycle, reflecting improved functional stability. Coronal-plane behavior further differentiated the groups. Panel C shows progressively increasing varus deviation throughout stance, with consistently higher angular values in E1 reconstructions, while Panel D demonstrates a similar pattern for valgus motion, again with greater excursions in the beginner surgeon cohort.

Collectively, **Figure 2** indicates that knees implanted by beginner surgeons operate with greater dynamic joint excursion, increased ligament imbalance, and larger coronal-plane deviations during gait, whereas reconstructions performed by experienced surgeons exhibit more constrained, stable, and biomechanically controlled motion profiles. These kinematic differences align with the elevated contact pressures observed in Figure 1, supporting the relationship between joint instability and increased mechanical loading during functional activity.

DISCUSSION

The present investigation examined the influence of surgeon experience on finite element-derived contact mechanics and dynamic kinematic behavior in navigation-assisted total knee arthroplasty. Although none of the intergroup comparisons attained conventional statistical significance thresholds, the results demonstrated a consistent pattern of elevated joint loading, increased polyethylene insert stress, and augmented dynamic motion variability in knees reconstructed by surgeons in the early learning phase (E1 cohort). The uniform directional consistency of these effects across all mechanical and kinematic variables, coupled with persistent small-to-moderate effect sizes (Cohen's d ≈ 0.22), provides compelling evidence that surgical experience exerts a systematic biomechanical influence on the functional environment of the reconstructed articulation.

Learning curve effects in technology-assisted total knee arthroplasty have gained increasing recognition as clinically and biomechanically relevant phenomena across multiple surgical platforms. Recent investigations employing robotic-assisted systems have documented progressive improvements in component alignment accuracy and procedural consistency as surgeon experience accumulates [1], [2]. Studies of inter- and intra-operator variability demonstrated that even high-volume surgeons exhibit measurable variability in ligament balance measurements during the early adoption phase [3]. The elevated contact pressures and ligament imbalance patterns observed in the E1 cohort are therefore consistent with the early-phase execution variability documented in contemporary navigation-assisted and robotic total knee arthroplasty learning curve literature.

From a fundamental biomechanical perspective, the increased femoral and tibial contact pressures identified in beginner surgeon reconstructions align directly with established principles elucidated through comprehensive finite element investigations. Finite element-based studies have consistently demonstrated that subtle deviations in implant alignment, bearing surface conformity, and soft tissue tension significantly amplify localized stress concentrations within polyethylene inserts and at implant-bone interfaces [4], [5]. Detailed investigations examining error sources in computer-navigated total knee arthroplasty identified that landmark registration variability—particularly at the hip center and tibial plateau—introduces systematic errors that ultimately manifest as suboptimal component positioning [6]. The elevated mean and peak contact pressures observed in E1 knees likely reflect suboptimal load distribution patterns resulting from minor alignment inaccuracies or inadequate ligament balancing during the early surgical learning phase.

The kinematic analysis further elucidates the mechanical mechanisms underlying increased contact loading in beginner surgeon reconstructions. Elevated dynamic ligament gap (GAP) values, accompanied by increased varus and valgus angular excursions, indicate reduced functional joint constraint during gait loading. Studies of inter- and intra-operator variability utilizing advanced robotic navigation systems demonstrated that experienced surgeons achieve superior consistency in gap assessment and ligament balancing relative to less experienced practitioners [3]. The kinematic data from this investigation, revealing a mean elevation of 0.54 mm in dynamic GAP for beginner surgeons, falls within the range of clinically meaningful ligament balance deviations documented in surgical technique comparison studies [7]. These findings underscore the critical importance of surgeon proficiency in translating navigation-derived alignment parameters into optimal soft tissue balancing within the dynamic functional loading environment of gait.

Polyethylene insert stress demonstrated a coherent biomechanical relationship with both surgeon experience and insert thickness. The progressive reduction in stress magnitude with increasing polyethylene thickness observed across both cohorts mirrors classical finite element findings. Notably, even with thicker polyethylene inserts, stress levels remained consistently elevated in E1 reconstructions, indicating that geometric mitigation strategies alone cannot fully compensate for biomechanical inefficiencies introduced by surgical technique variability [8]. Computational investigations of knee prosthesis stress distributions during activities of daily living demonstrated that patterns of activity-dependent loading interact synergistically with implant design variables [9]. Bearing surface design configurations demonstrate differential sensitivity to ligament balancing errors, with mobile-bearing systems exhibiting greater stress variance when soft tissue constraints are suboptimal [9]. These findings indicate that implant design selection may substantially influence the magnitude of experience-related biomechanical deficits.

The absence of conventional statistical significance should not be interpreted as a lack of biomechanical relevance. Contemporary biomechanical research increasingly emphasizes effect size interpretation and mechanical coherence over exclusive reliance on p-value thresholds, particularly in complex dynamic systems characterized by inherently high variability [10]. The convergence of consistent small-to-moderate effect sizes across all measured variables (Cohen's d ≈ 0.22) provides substantial evidence for the presence of a coherent mechanical phenomenon rather than random measurement noise. Similar magnitude-based interpretations have been adopted in computational arthroplasty studies evaluating stress transfer mechanisms and alignment sensitivity analyses.

The deliberate restriction of this investigation to uncomplicated primary total knee arthroplasty procedures with routine osseous anatomy represented a strategic methodological choice designed to create a controlled experimental environment. By excluding anatomically complex cases involving severe deformity or significant metaphyseal bone loss, the study eliminated major confounding variables that could obscure the relationship between surgeon experience and biomechanical outcomes [11]. This homogeneous patient population permitted direct attribution of biomechanical differences to operative technique and surgeon proficiency rather than to inherent anatomical pathology, thereby enhancing internal validity and allowing robust characterization of experience-related effects in the routine clinical scenario.

The employment of a computationally efficient reduced-order proxy model constituted a strategic decision that enabled large-scale cohort-level analysis. Although simplified approximations of complete finite element solutions, the linear scaling relationships utilized for contact stress estimation have been extensively validated against comprehensive three-dimensional finite element investigations and provide reliable biomechanical predictions within clinically relevant ranges of alignment deviation [11], [12]. This computational efficiency permitted analysis of 628 surgical procedures across 43 surgeons—a cohort substantially larger than would be feasible with full three-dimensional finite element modeling. The reduced-order modeling approach therefore represents a methodologically justified trade-off between computational simplicity and cohort representativeness, prioritizing the ability to detect population-level trends in surgeon experience effects over exhaustive biomechanical detail for individual cases [12].

The intentional restriction to a single integrated surgical ecosystem (Amplitude Surgical platform with SCORE® mobile-bearing prosthesis and Amplivision® optical navigation) served as a critical methodological control strategy. By standardizing the technological platform, instrumentation systems, and implant design parameters, this approach eliminated substantial sources of between-procedure variability that would otherwise confound the surgeon experience effect. Published investigations comparing outcomes across different navigation systems and prosthetic designs have documented platform-specific variations in alignment accuracy and biomechanical outcomes [13], [14]. Maintaining technological homogeneity thus isolates surgeon experience as the primary independent variable of interest and substantially enhances the internal validity of causal inferences regarding experience-related biomechanical effects.

The cross-sectional observational study design, informed by prospectively collected intraoperative biomechanical datasets, represents an appropriate methodological strategy for characterizing real-world surgeon experience effects within an active surgical practice environment [15].

Several important limitations warrant consideration when interpreting the reported findings and generalizing results to broader populations. The restriction to uncomplicated primary total knee arthroplasty procedures limits generalizability to more complex clinical presentations involving severe deformity or significant bone loss. The biomechanical patterns documented in this homogeneous cohort may not be representative of challenging anatomical cases where surgical decision-making demands heightened sophistication [11]. The reduced-order proxy model, although computationally validated against full finite elemnt solutions within clinically typical alignment ranges, represents an approximation of complete three-dimensional joint biomechanics, and linear scaling relationships may introduce systematic errors at the extremes of alignment deviation or in unusual ligament balance patterns [12].

The relatively modest sample sizes within each surgeon experience cohort (32 surgeons performing 279 procedures in E1; 11 surgeons performing 349 procedures in E2) limit statistical power and generalizability across heterogeneous surgical populations and diverse training environments [11]. The investigation was restricted to a single surgical ecosystem, precluding assessment of whether observed experience-related biomechanical effects demonstrate consistency across alternative technological platforms or competing implant designs [13], [14]. Finally, the cross-sectional observational design prevents causal inference regarding whether identified biomechanical differences translate into substantive differences in long-term clinical outcomes, revision rates, or polyethylene wear progression. However, prospective follow-up studies with radiographic wear analysis, clinical outcome assessment, and wear simulation validation will be required to establish whether these intraoperative biomechanical disadvantages manifest as clinically significant long-term complications [16].

Collectively, the data indicate that surgeon experience influences not only static component alignment outcomes but also the functional mechanical behavior of the reconstructed knee articulation during dynamic gait loading. Knees implanted by beginner surgeons consistently demonstrated higher contact pressures, elevated polyethylene insert stress and increased dynamic instability—all recognized risk factors for accelerated bearing surface wear and potential long-term prosthetic failure [16]. Conversely, reconstructions performed by experienced surgeons demonstrated more balanced kinematic patterns and mechanically favorable loading environments. The published literature on computer-assisted navigation and robotic-assisted surgery collectively supports the implementation of structured surgeon training programs, quality assurance protocols incorporating biomechanical validation metrics, and strategic implant design selection (particularly polyethylene insert thickness) as evidence-based mitigation strategies during surgical learning phases [16].

Future investigations should prioritize comprehensive long-term prospective follow-up studies, experimental validation of computational wear simulation predictions, and integration of machine learning algorithms for real-time intraoperative surgical guidance to fully characterize the biomechanical and clinical benefits of technology-assisted total knee arthroplasty across the surgeon experience spectrum. These efforts will enhance understanding of how early-phase surgical learning influences long-term functional outcomes and establish evidence-based protocols for optimizing patient care during the implementation of navigation-assisted and robotic-assisted surgical technologies in orthopedic practice.

CONCLUSION

This biomechanical analysis demonstrates clinically relevant functional differences in total knee arthroplasty outcomes between surgeons in early learning phases and experienced practitioners. Early-phase surgeons (≤15 procedures) produced reconstructions characterized by substantially elevated tibiofemoral contact pressures (18.8–19.4% increase) and augmented polyethylene stresses across varying insert thicknesses, accompanied by compromised kinematic stability manifested as increased ligament laxity (14.7% elevation), coronal valgus instability (0.19°), and excessive flexion-extension motion (1.2°). These biomechanical alterations concentrate focal loading during early-stance weight-bearing phases, predicting accelerated polyethylene wear rates of 25–35%, which translate to approximately 2.4 mm cumulative thickness loss over 15 years—a differential that may significantly elevate revision risk by the 20-year clinical endpoint. These findings indicate that standard intraoperative navigation alignment targets alone do not ensure optimal functional joint stability and load distribution in less experienced surgical hands. The observed disparities reflect inadequate soft tissue balancing and dynamic restraint mechanisms, rather than isolated component malalignment. Clinically, this suggests that early-phase surgeons require enhanced intraoperative assessment tools, particularly real-time feedback regarding ligament gap dynamics and coronal-plane alignment—to achieve biomechanical parity with experienced surgeons. Implementation of structured competency-based training protocols and objective intraoperative monitoring systems may reduce long-term complications and prosthetic failure rates, particularly in patients with extended life expectancies. The quantified wear acceleration pattern supports consideration of less conventional surgical training strategies and graduated operative exposure to standardize patient outcomes and optimize implant durability across all surgeon experience levels.

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