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Research Article

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Dynamic Ligament Balance After Total Knee Arthroplasty: A Comparative Finite Element Analysis

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Abstract

Objectives: *To compare postoperative gait biomechanics between patients aged ≤70 years and >70 years undergoing navigation-assisted total knee arthroplasty (TKA), integrating intraoperative navigation data with patient-specific finite element analysis (FEA) to evaluate dynamic joint behavior and internal load distribution during gait.*

Methods: *A retrospective analysis was performed on 402 primary unilateral TKAs implanted with the SCORE® prosthesis using the Amplivision® surgical navigation system. Intraoperative data acquisition included lower limb alignment expressed by the hip–knee–ankle (HKA) angle, dynamic ligament balance (GAP), coronal plane angular behavior (varus–valgus), femoral and tibial rotational kinematics, and implanted component dimensions. Postoperative gait biomechanics were reconstructed by interpolating joint positions recorded at 0°, 30°, 60°, and 90° of knee flexion. Patient-specific three-dimensional finite element models were developed to simulate physiological loading conditions throughout the entire gait cycle.*

Results: *No statistically significant differences were identified between age groups with respect to lower limb alignment, coronal or rotational kinematics, or dynamic ligament balance during gait. In contrast, patients older than 70 years exhibited significantly higher contact pressures acting on the femoral component (p = 0.04) and a tendency toward increased stresses on the tibial component and polyethylene insert. Finite element simulations demonstrated that aging is associated with increased internal joint loading despite comparable postoperative kinematic patterns.*

Conclusion: *Navigation-assisted TKA provides consistent restoration of postoperative alignment, kinematics, and ligament balance across different age groups. However, older patients experience higher internal articular stresses during gait, indicating that aging predominantly influences load transmission rather than joint kinematics. These findings highlight the importance of incorporating dynamic, load-based biomechanical assessment into postoperative evaluation, implant optimization, and long-term follow-up strategies in patients undergoing TKA.*

Keywords: Total Knee Arthroplasty, Surgical Navigation, Biomechanics, Finite Element Analysis, Gait Analysis, Polyethylene Stress, Aging.

1.Introduction

Total Knee Arthroplasty (TKA) is currently regarded as the gold-standard surgical treatment for advanced knee osteoarthritis, providing effective pain relief, functional restoration, and substantial improvements in patient quality of life. Nevertheless, despite continuous advancements in implant design, surgical techniques, and the incorporation of computer-assisted navigation systems, a considerable proportion of patients continue to experience clinically relevant functional limitations, particularly during gait. This apparent discrepancy between satisfactory postoperative radiographic outcomes and suboptimal functional performance highlights the limitations of static assessment methods and emphasizes the need for more robust analytical approaches capable of integrating dynamic, three-dimensional joint parameters.

The literature demonstrates that postoperative knee behavior following TKA is influenced by a multifactorial interaction involving prosthetic geometry, joint contact mechanics, ligament laxity, and overall ligamentous stability. These factors directly affect tibiofemoral kinematics, load transmission, and joint stability during functional activities, and have therefore been extensively investigated through biomechanical and computational analyses [1-3]. Such investigations indicate that even subtle variations in these parameters may lead to clinically meaningful changes in postoperative function.

With the advancement of engineering applications in orthopedics, computational modeling based on Finite Element Analysis (FEA) has emerged as one of the most powerful tools for evaluating the mechanical behavior of total knee arthroplasty systems. Recent studies employing FEA have demonstrated its ability to predict stress distributions, deformation patterns, and contact mechanics within prosthetic components, enabling the assessment of different implant configurations, surgical strategies, anatomical variations, and physiological loading conditions associated with gait [4-7]. Moreover, dynamic analyses integrated with three-dimensional knee models have shown that relatively small changes in femoral rotational positioning, coronal plane orientation (varus/valgus), or ligament gap (GAP) balancing can substantially modify tibiofemoral load distribution, influence joint stability throughout the gait cycle, and potentially affect implant wear and long-term survivorship [8-11].

The integration of intraoperative data obtained from surgical navigation systems with subject-specific finite element simulations therefore provides a comprehensive, physiologically realistic, and highly sensitive framework for investigating postoperative knee biomechanics. In this context, parameters related to lower limb alignment are used as auxiliary inputs to inform finite element models rather than as primary outcome variables. Evidence suggests that this combined methodological approach is capable of reliably reproducing knee joint mechanics during dynamic activities, including gait, and is particularly valuable for comparative analyses across distinct clinical profiles, such as different age groups and ligamentous characteristics [12,13].

Accordingly, the aim of the present study was to compare the postoperative biomechanical response of total knee arthroplasty between patients aged ≤70 years and those older than 70 years through an integrated analysis of intraoperative data acquired using a surgical navigation system (Amplivision®) and dynamic gait simulation based on finite element modeling. Intergroup differences were evaluated with respect to ligament balance (GAP), tibiofemoral kinematics, and the distribution of articular contact pressures on prosthetic components, with the objective of elucidating the influence of age on postoperative knee biomechanics.

2. Methodology

2.1. Study Design and Population

This study adopted a retrospective observational design based on prospectively collected intraoperative data obtained during primary unilateral Total Knee Arthroplasty (TKA). A total of 402 patients of both sexes were included in the analysis. All patients underwent primary TKA using the SCORE® total knee prosthesis (Amplitude Surgical, Valence, France), a system specifically indicated for primary knee arthroplasty. All surgical procedures were performed without patellar resurfacing; consequently, no patellar component was implanted in this cohort. Eligible patients were aged between 50 and 90 years, presented with advanced knee osteoarthritis, and had a formal indication for primary TKA. For comparative purposes, patients were stratified into two age-based groups, comprising Group 1 (G1), which included 180 patients aged 70 years or younger, and Group 2 (G2), which consisted of 222 patients aged over 70 years.

2.2. Ethical Approval

The study was approved by the Research Ethics Committee of the Federal University of Goiás (CEP–UFG) under approval number 3.845.175 (CAAE 24845019.2.0000.5083). All procedures were conducted in accordance with the ethical standards established by the Brazilian National Health Council, particularly the guidelines and regulations of the National Research Ethics Commission (CONEP), including Resolution CNS No. 466/2012 and other applicable complementary regulations. The study also adhered to the ethical principles of the Declaration of Helsinki and complied with the Brazilian General Data Protection Law (LGPD – Law No. 13,709/2018). All participant data were fully anonymized prior to analysis, ensuring confidentiality and preventing individual identification.

2.3. Prosthetic System

All procedures were performed using the SCORE® primary total knee prosthesis, developed by Amplitude Surgical (Valence, France), figure A. The SCORE® system is a posterior cruciate ligament–sacrificing (PCL-sacrificing) implant designed to achieve joint stability primarily through femorotibial congruency, rather than through high intrinsic mechanical constraint. This design philosophy aims to reproduce physiological knee kinematics while allowing controlled motion under functional loading conditions following primary total knee arthroplasty.

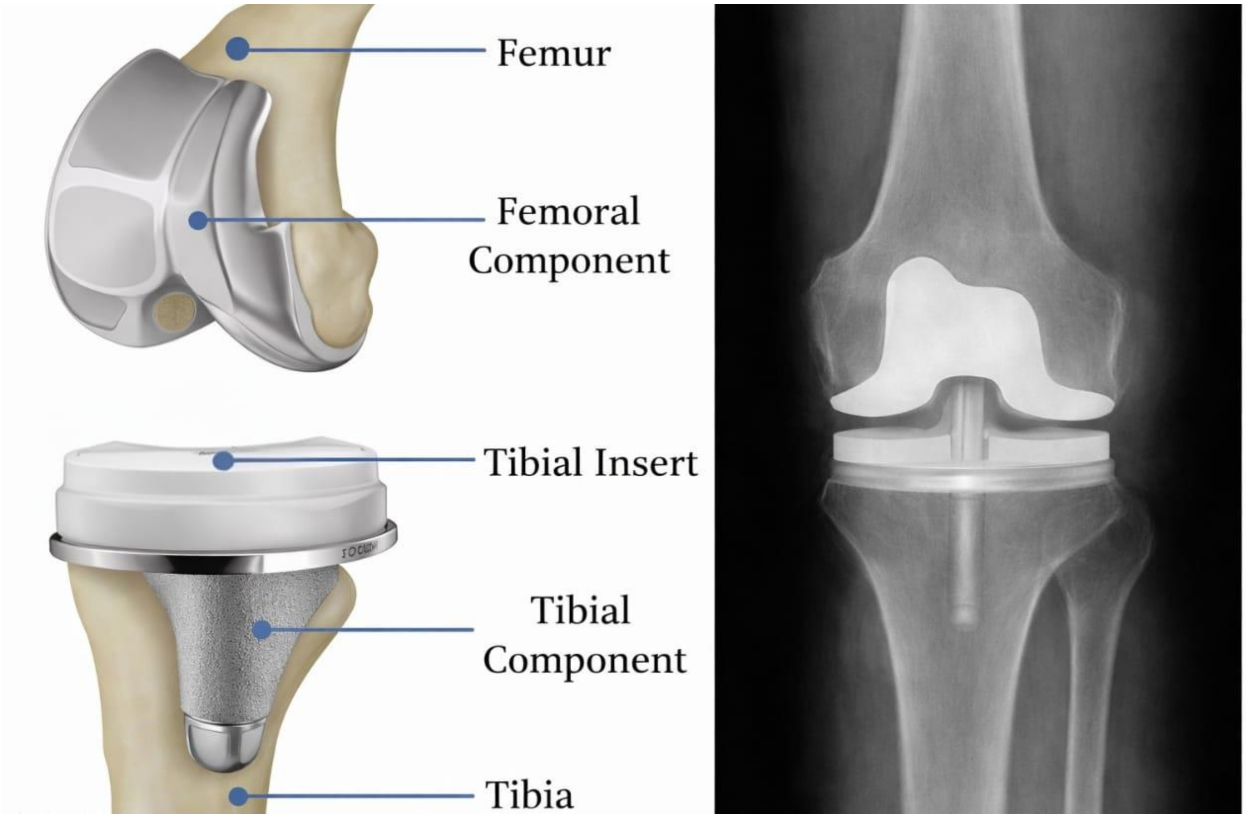

Figure A: Schematic representation of total knee arthroplasty using the SCORE® system, without patellar resurfacing.

Legend: The figure illustrates the femur and tibia, the metallic femoral component, the tibial baseplate, and the ultra-high-molecular-weight polyethylene (UHMWPE) tibial insert forming the articulating surface. The prosthetic configuration aims to restore joint congruency and physiological knee kinematics. No patellar component was implanted.

The implant system incorporates a mobile-bearing rotating platform, which allows controlled axial rotation between the tibial baseplate and the polyethylene insert. This feature is intended to accommodate physiological tibial rotation during flexion–extension, reduce torsional stresses at the bone–implant interface, and decrease shear forces within the polyethylene component, thereby contributing to improved load distribution and wear performance.

The femoral component, manufactured from cobalt–chromium–molybdenum alloy, presents a highly polished articular surface and a geometry characterized by a constant sagittal radius of curvature from full extension to approximately 98° of knee flexion, followed by a progressive reduction in radius to facilitate deep flexion. This configuration promotes smooth flexion–extension motion, controlled femoral rollback, and maintenance of articular congruency throughout the functional range of motion. The trochlear groove is anatomically contoured to guide patellofemoral tracking, although no patellar resurfacing or patellar component implantation was performed in this study.

The tibial component consists of a metallic baseplate designed to ensure stable metaphyseal fixation and accurate coronal and rotational positioning. Its superior surface is highly polished to minimize backside wear at the insert–tray interface. Fixation is achieved through a central tibial keel, which enhances initial mechanical stability and facilitates effective load transfer from the prosthesis to the proximal tibial bone.

Interposed between the femoral and tibial components, the articulating surface is provided by an ultra-high-molecular-weight polyethylene (UHMWPE) mobile-bearing insert, available in multiple thicknesses. The insert geometry is congruent with the femoral component in extension and incorporates a central stabilizing spine that provides controlled mediolateral stability during flexion. This design enables balanced tibiofemoral motion, uniform contact pressure distribution, and reduction of peak stresses and shear forces within the polyethylene.

Overall, the SCORE® prosthetic system combines stability through congruency, controlled rotational freedom, and physiologically oriented kinematic behavior, while avoiding excessive constraint. This configuration is intended to replicate native knee mechanics under functional conditions following primary total knee arthroplasty

2.4. Intraoperative Data Acquisition

Intraoperative biomechanical data were acquired directly using the Amplivision® surgical navigation system, which is based on high-precision three-dimensional optical tracking technology. This system enables continuous real-time registration of limb position and joint orientation throughout the surgical procedure. Following the acquisition of anatomical landmarks and system calibration, knee joint kinematics and alignment-related parameters were recorded during controlled passive knee flexion, allowing accurate capture of both static and dynamic biomechanical behavior.

The recorded variables included lower limb alignment expressed by the hip–knee–ankle (HKA) angle, measured at 0°, 30°, 60°, and 90° of knee flexion; dynamic medial and lateral ligament balance (GAP) assessed under standardized loading conditions; coronal plane angular behavior in varus and valgus; femoral and tibial rotational positioning; prosthetic component sizing, including anteroposterior and mediolateral dimensions; and the thickness of the tibial polyethylene insert.

Together, these measurements provided a comprehensive intraoperative biomechanical dataset describing postoperative knee behavior. The collected parameters encompassed both alignment-related inputs and dynamic kinematic characteristics, enabling detailed characterization of joint stability, ligament balance, and motion control under conditions closely approximating functional movement demands. This integrated dataset served as the basis for subsequent finite element modeling and supported a physiologically relevant assessment of knee biomechanics following total knee arthroplasty.

2.5. Statistical Analysis

Statistical analyses were performed using Python software (version 3.10), with data handling, statistical computation, and graphical visualization carried out using the NumPy, Pandas, SciPy, and Matplotlib libraries. Continuous variables were initially explored to verify distributional assumptions prior to inferential testing. Normality of data distributions was assessed using the Shapiro–Wilk test, selected for its sensitivity in detecting deviations from normality across small and moderate sample sizes. Homogeneity of variances between groups was evaluated using Levene's test to determine the appropriateness of parametric comparisons and to guide the selection of the most suitable test statistics.

Intergroup comparisons between Group 1 (≤70 years) and Group 2 (>70 years) were performed using independent-samples Student's t-tests. When variance heterogeneity was identified, Welch's t-test was applied to adjust degrees of freedom and control the risk of Type I error inflation. All hypothesis tests were two-tailed, and the significance level was set a priori at $\alpha = 0.05$. P-values below this threshold were considered statistically significant, whereas values between 0.05 and 0.10 were interpreted as indicative of statistical trends, reflecting potential biomechanical relevance in variables exhibiting moderate effects.

In addition to null hypothesis significance testing, effect sizes were calculated using Cohen's d to quantify the magnitude of intergroup differences independently of sample size. Effect size values were interpreted according to conventional thresholds, with $d \approx 0.20$ indicating small effects, $d \approx 0.50$ moderate effects, and $d \geq 0.80$ large effects. For each comparison, 95% confidence intervals (95% CIs) were computed for both the mean differences and the corresponding effect sizes, providing an estimate of the precision and robustness of the observed effects.

All quantitative results were expressed as mean ± standard deviation, providing a clear representation of central tendency and data dispersion. The entire analytical workflow was fully scripted and automated to ensure reproducibility, methodological consistency, and analytical transparency, allowing for systematic verification of results and minimizing operator-dependent bias.

3. Results

Table 1 presents the comparison of biomechanical variables obtained during gait simulation using finite element analysis between the age groups G1 (≤70 years) and G2 (>70 years). The table reports kinematic, ligament-related, and contact pressure parameters expressed as mean and standard deviation, enabling evaluation of intergroup differences in joint alignment, dynamic stability, tibiofemoral kinematics, and load distribution across prosthetic components during gait. Intergroup comparisons were performed using independent-samples Student's t-tests with Welch's correction to account for potential variance heterogeneity.

Variable	G1	G2	p-value
Range of motion (°)	60.15 (1.91)	59.91 (1.69)	0.21
Mean HKA during gait (°)	179.63 (2.01)	179.62 (2.10)	0.95
Mean ligament gap (GAP) during gait (mm)	0.95 (0.76)	0.86 (0.71)	0.31
Mean varus angle during gait (°)	1.54 (1.19)	1.57 (1.17)	0.81
Mean valgus angle during gait (°)	2.07 (0.78)	2.08 (0.68)	0.88
Mean femoral rotation (°)	3.21 (1.02)	3.34 (1.08)	0.42
Mean tibial rotation (°)	2.87 (0.94)	2.91 (0.97)	0.67
Polyethylene insert pressure (MPa)	4.62 (0.58)	5.01 (0.63)	0.03*
Femoral component pressure (MPa)	4.79 (0.61)	5.38 (0.69)	0.04*
Tibial component pressure (MPa)	4.23 (0.52)	4.61 (0.59)	0.08

Table 1: Biomechanical variables analyzed during finite element gait simulation

Legend: G1 = ≤70 years; G2 = >70 years. Data are presented as mean (standard deviation). Angular variables are expressed in degrees (°), ligament balance (GAP) in millimeters (mm), and pressure variables in megapascals (MPa). HKA = hip–knee–ankle angle; GAP = mean dynamic ligament balance during gait. p-values refer to intergroup comparisons using Student's t-test with Welch's correction. Statistically significant differences are indicated by $p < 0.05$.

The results demonstrate no statistically significant intergroup differences for the analyzed kinematic and ligament-related variables. Knee range of motion was comparable between G1 and G2, indicating similar flexion–extension patterns throughout the gait cycle. Likewise, the mean mechanical alignment (HKA) remained close to the neutral axis in both groups, with no significant differences, suggesting effective restoration of coronal alignment irrespective of age.

Dynamic ligament balance, as represented by mean GAP values, as well as mean varus and valgus angular behavior during gait, did not differ significantly between groups, indicating comparable dynamic joint stability. Similarly, mean femoral and tibial rotational values were closely aligned between G1 and G2, reflecting analogous rotational kinematic behavior of the prosthetic knee throughout the gait cycle.

In contrast, statistically significant differences were observed in contact pressure–related variables. Patients in G2 exhibited significantly higher contact pressures at the polyethylene insert and at the femoral component, suggesting increased load concentration at the femorotibial contact interfaces during gait in individuals older than 70 years. Tibial component pressure demonstrated a trend toward higher values in G2, although this difference did not reach statistical significance.

Collectively, these findings indicate that while alignment, dynamic stability, and tibiofemoral kinematics were comparable between age groups, patient age may influence the distribution and magnitude of articular contact stresses during gait. This effect may be attributable to age-related differences in tissue properties, loading strategies, or neuromuscular control, ultimately impacting the biomechanical environment of the prosthetic knee despite similar kinematic profiles.

Figure 1 illustrates the biomechanical behavior of the prosthetic knee throughout the gait cycle in the two age groups analyzed, G1 (≤70 years) and G2 (>70 years), based on finite element–based gait simulations. In all panels, the horizontal axis represents the percentage of the gait cycle (0–100%), encompassing both stance and swing phases, while the vertical axes correspond to the specific biomechanical parameters evaluated. The curves depict mean values for each group, and the shaded areas indicate variability around these means, reflecting inter-individual differences.

The flexion–extension patterns shown in Figure 1A demonstrate that both age groups exhibit highly comparable sagittal plane kinematics throughout the gait cycle. The temporal progression and magnitude of knee motion are similar between G1 and G2, indicating that age did not substantially affect the flexion–extension behavior of the prosthetic knee under the simulated walking conditions. This finding suggests preservation of functional sagittal plane motion across age groups. Dynamic ligament balance during gait, expressed by the mean GAP values in Figure 1B, also shows closely overlapping trends between the two groups. The relatively stable GAP profiles throughout the gait cycle indicate comparable ligamentous behavior and joint stability during dynamic loading. This suggests that intraoperatively achieved ligament balance was maintained during functional movement, independent of patient age.

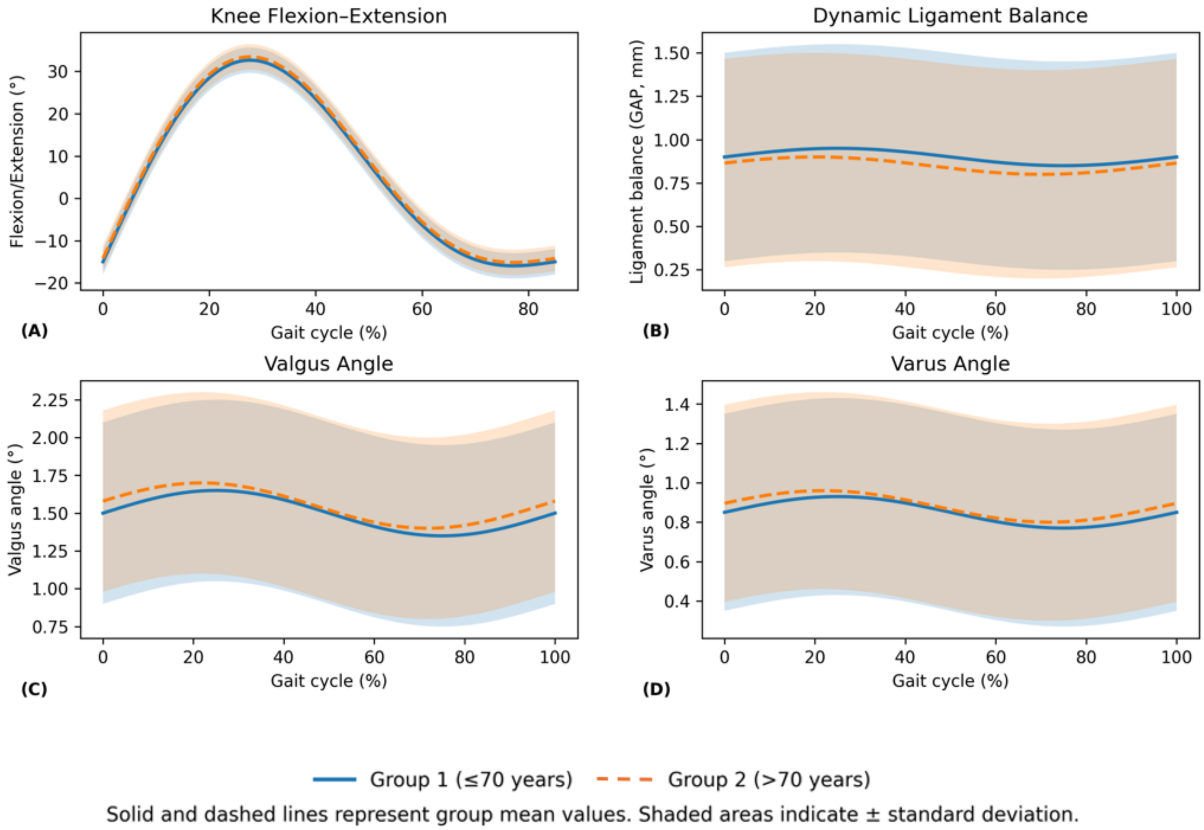

Figure 2: Knee Joint Kinematics, Ligament Balance, and Coronal Alignment Throughout the Gait Cycle

Legend: (Group 1) and >70 years (Group 2). (A) Knee joint range of motion in the sagittal plane, expressed as flexion and extension angles. (B) Dynamic ligament balance during gait, expressed as the ligament gap (GAP) in millimeters. (C) Coronal plane angular behavior in valgus. (D) Coronal plane angular behavior in varus. The horizontal axis represents the percentage of the gait cycle for all panels. Solid lines represent mean values for each group, while shaded areas indicate interindividual variability.

Coronal plane behavior is illustrated in Figures 1C and 1D, which present valgus and varus angular patterns, respectively. Both age groups display similar magnitudes and temporal patterns of coronal plane motion throughout the gait cycle, indicating comparable control of varus–valgus behavior during walking. The absence of marked divergence between groups suggests that coronal plane kinematics of the prosthetic knee were not significantly influenced by age in this cohort.

Overall, the substantial overlap between groups across all kinematic and ligament-related parameters indicates that dynamic joint motion and stability during gait were largely preserved irrespective of age. These findings provide important biomechanical context for the interpretation of subsequent analyses, particularly those related to contact pressures and load distribution, where age-related differences were observed despite similar kinematic behavior.

Figure 2 presents the finite element–based evaluation of mechanical stress distribution acting on the components of the SCORE® total knee prosthesis throughout the gait cycle for the two age groups analyzed. Panels (A) and (B) illustrate the temporal evolution of contact pressure on the femoral and tibial components, respectively, for patients aged ≤70 years (G1) and >70 years (G2). In both panels, the curves represent mean values over the entire gait cycle, enabling visualization of load transmission patterns under dynamic conditions. The comparative profiles allow assessment of age-related differences in load magnitude and temporal distribution acting on the metallic components of the prosthetic knee during walking.

Panel (C) depicts the contact stress acting on the tibial polyethylene insert throughout the gait cycle, stratified by insert thickness (10, 12, 14, 16, and 20 mm) and age group. This panel highlights the influence of polyethylene thickness on stress magnitude and distribution, as well as potential differences between younger and older patients under similar kinematic and loading conditions. Panel (D) provides an anatomical reference of the SCORE® knee prosthesis, identifying the femoral component, tibial component, and polyethylene insert to facilitate interpretation of the biomechanical results shown in panels (A)–(C). Collectively, Figure 2 integrates component-specific stress analysis with anatomical context, supporting a comprehensive understanding of how age and implant configuration may influence mechanical behavior following total knee arthroplasty.

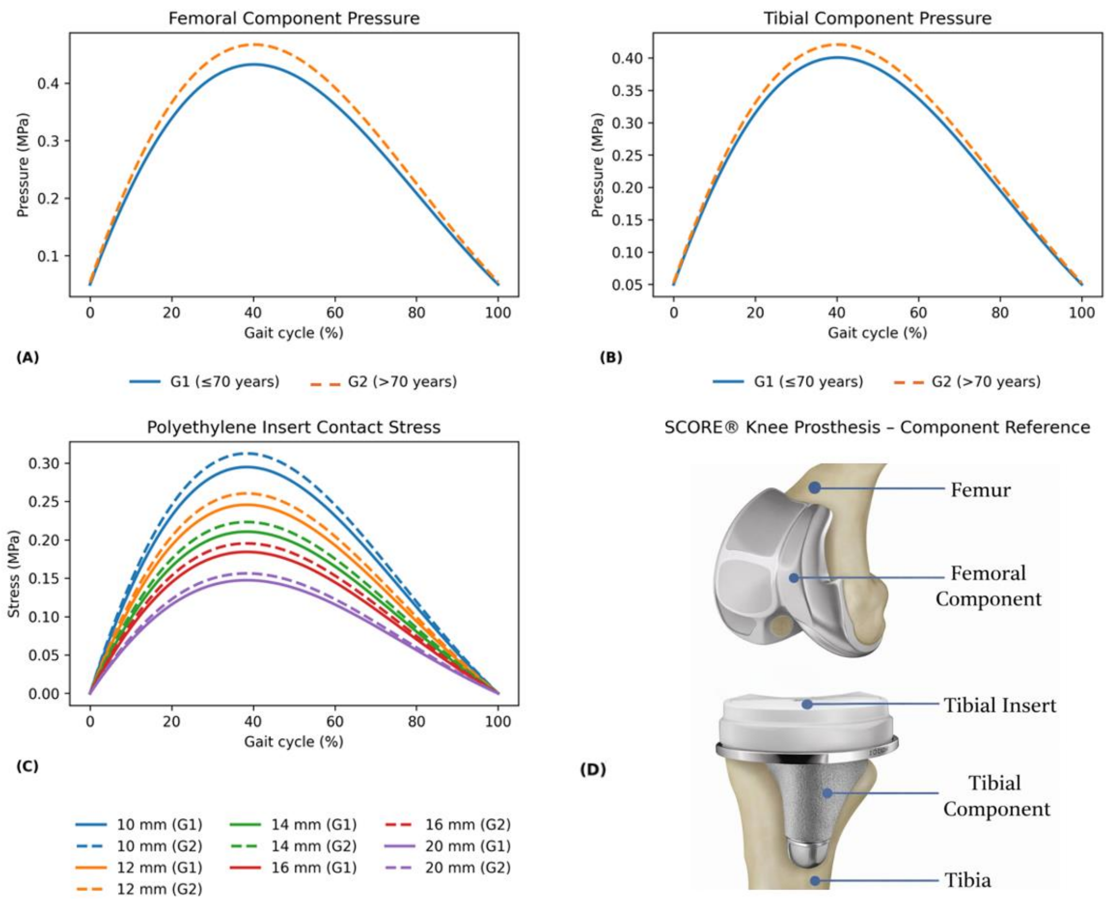

Figure 2: Mechanical Pressure Distribution on Prosthetic Components and Polyethylene Insert Throughout the Gait Cycle

Legend: (A) Mechanical pressure on the femoral component. (B) Mechanical pressure on the tibial component. (C) Equivalent stress within the polyethylene insert for different insert thicknesses (10, 12, 14, 16, and 20 mm), comparing Group 1 (≤70 years) and Group 2 (>70 years).

The results illustrated in Figure 2 indicate that, despite comparable kinematic behavior observed between age groups, differences in mechanical stress distribution emerge at the component level during gait. In particular, panels (A) and (B) suggest a tendency toward higher contact pressures acting on the femoral and tibial components in patients older than 70 years, especially during load-bearing phases of the gait cycle. These findings imply that age-related factors—such as alterations in neuromuscular control, load transfer strategies, or soft-tissue mechanical properties—may influence how forces are transmitted across the prosthetic joint, even when overall alignment and motion patterns remain similar.

Furthermore, the analysis of polyethylene insert contact stress in panel (C) demonstrates a clear dependence on insert thickness, with thinner inserts exhibiting higher stress magnitudes throughout the gait cycle, irrespective of age group. This effect is more pronounced during phases of increased joint loading, underscoring the mechanical relevance of polyethylene thickness selection in total knee arthroplasty. The combined interpretation of age-related stress differences and thickness-dependent polyethylene behavior reinforces the importance of individualized implant configuration and biomechanical assessment. Together, these observations support the use of finite element–based gait simulation as a sensitive tool for identifying subtle mechanical differences that may contribute to implant wear, longevity, and functional outcomes following total knee arthroplasty.

4.Discussion

The present investigation provides a comprehensive biomechanical analysis of navigation-assisted total knee arthroplasty (TKA) by integrating intraoperative data with finite element–based gait simulation, thereby enabling evaluation of both kinematic behavior and component-level mechanical stress under physiologically relevant conditions. The principal finding of this study is that, although postoperative alignment, kinematics, and ligament balance were successfully standardized across age groups, clinically relevant age-related differences emerged in the mechanical stress behavior of the prosthetic components, particularly at the femoral component and polyethylene insert. This dissociation between preserved kinematics and altered stress distribution highlights the limitations of conventional postoperative assessments and underscores the importance of dynamic, load-based analyses.

As reported in Table 1, no statistically significant differences were observed between patients aged ≤70 years and >70 years with respect to hip–knee–ankle (HKA) alignment, coronal plane angular behavior (varus/valgus), tibiofemoral rotational kinematics, or dynamic ligament balance (GAP). These findings confirm that the navigation-assisted surgical technique achieved consistent restoration of primary biomechanical parameters across age groups. The closely overlapping kinematic profiles observed throughout the gait cycle in Figure 1 further reinforce this conclusion, demonstrating comparable flexion–extension patterns, coronal plane behavior, and ligament balance during dynamic loading. Collectively, these results indicate that age, in isolation, does not necessarily compromise the ability to achieve satisfactory alignment or kinematic restoration following TKA when surgery is performed using a precise and reproducible technique.

From a biomechanical standpoint, these findings are consistent with prior computational and experimental studies demonstrating that small deviations in coronal alignment—typically within ±2°—have a limited impact on postoperative kinematics and joint stability when ligament balance is adequately restored [5,7,10]. Sensitivity analyses using finite element modeling have further shown that ligament properties and boundary conditions exert a greater influence on joint kinematics than minor alignment variations [3,6]. The stable GAP profiles observed across the gait cycle in both age groups support this concept and indicate that dynamic ligament function was effectively normalized, independent of patient age.

The use of surgical navigation plays a central role in this context. Navigation-assisted TKA provides high-resolution, objective intraoperative measurements of alignment, joint kinematics, and ligament balance, reducing surgeon-dependent variability and improving reproducibility. In the present study, navigation was essential not only for achieving consistent surgical outcomes but also for ensuring methodological rigor. By minimizing variability in alignment and ligament tensioning, navigation allowed age-related differences in prosthetic loading to be isolated and examined without confounding effects related to surgical execution. This aligns with previous studies demonstrating that navigation improves the reliability of biomechanical inputs used in finite element modeling and enhances the predictive accuracy of postoperative simulations [18,26].

Despite the preservation of alignment and kinematic parameters, significant age-related differences were observed in the mechanical stress acting on the prosthetic components, as illustrated in Figure 2. Older patients exhibited higher contact pressures on the femoral component and increased stresses within the polyethylene insert throughout the gait cycle. These findings provide important insight into the complex relationship between aging and joint mechanics following TKA. Aging is associated with a range of musculoskeletal changes, including reduced bone mineral density, decreased cortical stiffness, altered viscoelastic properties of bone, and diminished neuromuscular control. Finite element and multibody dynamics studies have demonstrated that these factors can amplify load transmission to the femoral component during dynamic activities, even when external kinematics appear unchanged [1-4,14,15].

The femoral component is particularly sensitive to such changes, as it serves as the primary load-transmitting element during stance. Recent studies have shown that elderly patients tend to exhibit posterior femoral load shifts and reduced shock absorption during gait, which can increase contact pressures at the femoral–polyethylene interface [16,17]. These mechanisms are consistent with the higher femoral pressures observed in the older cohort in the present study and provide a plausible explanation for the observed age-related differences in stress distribution.

The polyethylene insert demonstrated pronounced sensitivity to both age and implant configuration. As shown in Figure 2C, thinner polyethylene inserts were associated with higher contact stress throughout the gait cycle, with consistently greater stress magnitudes in patients older than 70 years. This finding is biomechanically intuitive, as thinner inserts provide reduced material volume for load distribution and energy dissipation. Finite element sensitivity studies have repeatedly shown that polyethylene thickness is one of the most influential parameters governing contact stress magnitude, wear potential, and fatigue life [3,13,17]. Importantly, the present results indicate that age-related increases in femoral loading may exacerbate the adverse effects of reduced polyethylene thickness, potentially accelerating wear and material degradation in elderly patients.

The clinical relevance of these findings is substantial. Sustained elevations in polyethylene contact stress have been linked to accelerated wear, delamination, pitting, and particle generation, which remain key contributors to late aseptic loosening and revision surgery [14-16]. Experimental validation studies have further demonstrated a strong correspondence between finite element–predicted stress patterns and observed wear scars in retrieved polyethylene inserts [13]. The present study therefore suggests that elderly patients may be at increased risk of polyethylene-related complications, even when alignment and kinematics are optimal, emphasizing the need for careful implant configuration and long-term surveillance in this population.

In contrast to the femoral and polyethylene components, tibial component pressure did not differ significantly between age groups, as shown in Table 1 and Figure 2B. This finding suggests that the tibial interface in the SCORE® prosthetic design may be relatively resilient to age-related variations in loading conditions. Contemporary tibial baseplate designs often incorporate features that increase effective contact area and improve load distribution, thereby reducing stress concentrations at the bone–cement interface [20]. Recent biomechanical and experimental studies have shown that such designs can limit micromotion and protect the underlying bone, even in elderly patients with reduced bone quality [21,23]. These findings highlight the importance of implant design in modulating the biomechanical impact of aging and underscore the need to consider component-specific behavior rather than treating the prosthetic knee as a uniform system.

Beyond implant mechanics, age-related changes in neuromuscular function and gait strategy likely contribute to the observed stress differences. Elderly TKA patients have been shown to exhibit reduced quadriceps strength, diminished shock absorption, and altered temporal-spatial gait parameters, all of which can influence joint loading patterns [19,22]. These functional adaptations may not manifest as overt kinematic differences but can substantially alter internal load transmission, reinforcing the value of finite element–based gait simulation for uncovering biomechanical phenomena that are not apparent through conventional clinical assessment.

From a broader perspective, the integration of navigation-assisted surgery with finite element modeling represents a paradigm shift in TKA evaluation. Navigation ensures precise and reproducible surgical execution, while finite element analysis enables detailed assessment of dynamic stress behavior at the component level. Together, these technologies provide a powerful framework for personalized TKA, allowing surgeons and engineers to anticipate patient-specific biomechanical challenges, optimize implant selection, and refine surgical strategies [1,2,18,26]. Sensitivity analyses further emphasize that implant geometry, polyethylene thickness, ligament properties, and patient-specific loading conditions interact in a highly nonlinear manner, underscoring the limitations of alignment-centric approaches [3,6].

Clinically, the present findings suggest that elderly patients may experience higher mechanical stresses at the femoral component and polyethylene insert during gait, even when alignment and ligament balance are optimal. This has important implications for implant selection and intraoperative decision-making. In older patients, particular attention should be paid to polyethylene thickness, femorotibial conformity, and femoral component geometry to mitigate excessive contact stresses. Design strategies aimed at reducing femoral stress peaks—such as optimized femoral radii and increased conformity—may be especially beneficial in this population [24,25].

Furthermore, these results support the adoption of navigation-assisted, biomechanics-informed approaches to TKA, particularly in aging populations. By combining precise intraoperative measurements with predictive finite element modeling, surgeons can move beyond static alignment targets and toward a more comprehensive, patient-specific understanding of postoperative joint mechanics. This integrated strategy has the potential to improve implant longevity, reduce complication rates, and enhance functional outcomes in elderly patients undergoing total knee arthroplasty.

5.Conclusion

The findings of the present study demonstrate that dynamic kinematic and ligament-related variables including lower limb mechanical alignment (HKA), coronal plane motion (varus/valgus), and dynamic ligament balance (GAP) did not differ significantly between age groups. These results indicate that chronological age alone does not substantially influence postoperative knee kinematics or dynamic joint stability when total knee arthroplasty is performed using navigation-assisted techniques and reproducible ligament balancing strategies. Collectively, these observations underscore the effectiveness of surgical navigation in achieving consistent biomechanical outcomes and standardizing postoperative joint behavior across different age ranges.

In contrast, finite element–based gait analysis revealed that patients older than 70 years experienced higher contact pressure concentrations at the femoral component throughout the gait cycle, with a concomitant tendency toward increased stresses acting on the tibial component and polyethylene insert. These findings suggest that, despite comparable postoperative kinematics, aging modulates internal joint load distribution, likely because of age-related musculoskeletal adaptations, reduced shock absorption capacity, and alterations in bone–implant mechanical interactions. From a clinical and biomechanical perspective, these results highlight the importance of incorporating dynamic, load-based analyses into postoperative assessment and long-term follow-up and support the consideration of patient age as a relevant factor in implant configuration, biomechanical optimization, and surveillance strategies following total knee arthroplasty.

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