Comparative Analysis of Contact Pressure Distribution in Conventional vs. Robotic-Assisted Unicompartmental Knee Arthroplasty: Insights from In Silico Modeling and Cadaveric Studies

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INTRODUCTION: Unicompartmental knee arthroplasty (UKA) is a widely used alternative to total knee arthroplasty (TKA) for patients with isolated compartment osteoarthritis (OA), most often in the medial compartment[1,2]. While UKA offers benefits such as faster recovery, preserved bone stock, and improved range of motion[3-8], it also carries higher long-term failure rates compared to TKA, primarily due to mechanical loosening from malalignment or poor knee balancing[9-13]. Suboptimal load distribution, especially in the lateral compartment, contributes to these failures[14]. Although robotic-assisted UKA has improved alignment precision[5,6], clinical outcomes remain inconsistent. Refining techniques for proper postoperative load distribution is critical to improve implant longevity and joint function. Proper implant positioning and ligament balance are critical, as valgus or varus malalignment increases compartmental stress and implant wear[5,7,11]. Ligament deficiencies, particularly involving the ACL or MCL, can exacerbate these stresses[6]. Finite element (FE) modeling has emerged as a powerful tool to assess implant mechanics, load distribution, and surgical planning[4-8]. These models simulate physiologic loading without the limitations of cadaveric studies. In this study, tibiofemoral contact pressure was compared in cadaveric knees treated with either conventional or robotic-assisted UKA, and a validated FE model was developed to assess biomechanical behavior post-UKA. The primary goal of this research is to improve surgical planning and patient outcomes by refining knee balancing and predicting joint mechanics using computational methods.

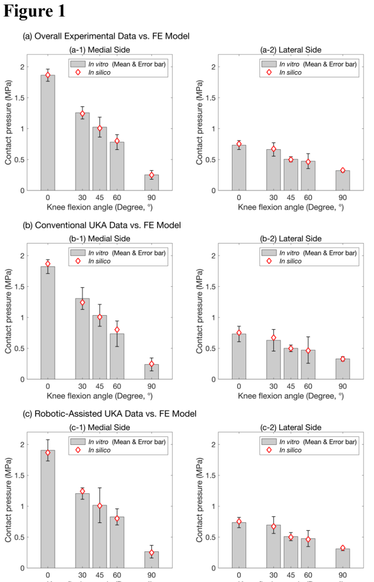
METHODS: Sixteen fresh-frozen cadaveric lower limb specimens were subjected to UKA using either standardized cutting guides (conventional UKA, n=8) or CORI robotic-assisted technology (n=8). Demographic data showed similar baseline characteristics: conventional UKA (mean age 80.13 ± 8.54 years, BMI 26.49 ± 4.98), robotic-assisted UKA (mean age 78.00 ± 10.80 years, BMI 23.13 ± 5.79), with no significant BMI difference ($p=0.234$). Male-to-female and left-to-right ratios were 1:1 in both groups. Tibiofemoral contact pressures, forces, and contact areas were measured in both the medial (implanted) and lateral (native) compartments using FlexiForce sensors (Tekscan) at controlled knee flexion angles (full extension at 0°, and flexion at 30°, 45°, 60°, and 90°). Statistical comparisons were conducted on the obtained biomechanical parameters between groups. Additionally, FE simulations replicating the experimental conditions were performed using Abaqus 2022 (Dynamic/Explicit), which facilitated the validation of the FE model against the experimental data.

RESULTS: As the cadaveric knee joint moved from full extension (0°) to 90° of flexion, contact pressure in the medial compartment treated with UKA significantly decreased from 1.864 MPa to 0.252 MPa ($p < 0.05$). A comparable statistically significant reduction was observed in the intact lateral compartment, with pressure decreasing from 0.733 MPa to 0.320 MPa ($p < 0.05$). However, no statistically significant differences were found between the conventional and robotic-assisted UKA techniques in terms of contact pressure across flexion angles ($p > 0.05$). The FE model exhibited a strong correlation with the in vitro measurements (Figures 1 and 2), with r^2 values of 0.9994 for the medial compartment and 0.9962 for the lateral compartment, indicating strong agreement with observed trends. When analyzed by surgical technique, the conventional UKA group yielded r^2 values of 0.9922 (medial) and 0.9923 (lateral), whereas the robotic-assisted UKA group showed r^2 values of 0.9977 (medial) and 0.9887 (lateral). These findings suggest that the FE model effectively replicates experimental contact pressure behavior and may be particularly suitable for simulating outcomes in conventional UKA. Notably, while there was no significant difference in the correlation in the medial region between the robot-assisted group and the traditional group, the correlation with the measurement values in the lateral region was higher in the conventional group. This underscores the potential of the FE model as a valuable tool for refining conventional surgical approaches and enhancing preoperative planning.

DISCUSSION: This study demonstrates that conventional and robotic-assisted UKA techniques yield similar tibiofemoral contact pressure profiles across flexion, with significant reductions in pressure from 0° to 90° in both compartments. Persistent asymmetry in load distribution may contribute to lateral compartment degeneration and increased revision risk, underscoring the importance of achieving precise tibiofemoral alignment and mediolateral balance. The strong correlation between in vitro and FE model results supports the accuracy of in silico simulations for orthopedic applications. FE modeling offers a scalable, cost-effective alternative to cadaveric testing, enabling preoperative simulation of surgical parameters and implant designs. This could promote personalized arthroplasty by accounting for patient-specific anatomy. While current models reflect normative ligament conditions, future studies should explore pathological scenarios such as ACL or MCL deficiency, known to alter contact stresses. Limitations include the inability of cadaveric testing to replicate in vivo biomechanics and the current model's restriction to time-zero loading. Nonetheless, the validated FE model provides a promising tool for enhancing UKA planning and optimizing long-term outcomes.

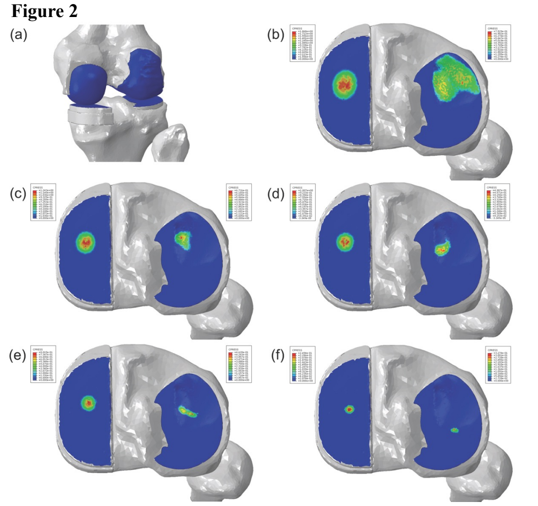
SIGNIFICANCE/CLINICAL RELEVANCE: This study validates a model specifically calibrated against real-world cadaveric and sensor data. Integrating FE modeling into clinical workflows and robotic-assisted platforms may reduce revision risk by optimizing mediolateral balance and tibiofemoral contact mechanics, thereby improving long-term UKA outcomes and extending implant longevity.

Figure 1



REFERENCES: [1] Levy et al., 2023. [2] Fratini et al., 2025. [3] Robertsson et al., 1999. [4] Koh et al., 2020. [5] Koh et al., 2020. [6] Kwon et al., 2020. [7] Kang et al., 2018. [8] Zhang et al., 2023. [9] Hansen et al., 2019. [10] Obermayr et al., 2024. [11] Ekhtiari et al., 2021. [12] Heyse et al., 2017. [13] Kannan et al., 2021. [14] Kuipers et al., 2010.

Figure 2



IMAGES AND TABLES:

Figure 1: Compared the results of the overall in vitro (a), conventional UKA (b), and robotic-assisted UKA (c) experimental data with the FE model result depending on the knee flexion angles (0°, 30°, 45°, 60°, and 90°).

Figure 2: The validated UKA FE model using the in-vitro experiment data (a) and contact pressure distributions at knee flexion angles of 0° (b), 30° (c), 45° (d), 60° (e), and 90° (f) in the FE simulation.