

A MONTE CARLO SENSITIVITY ANALYSIS OF ANATOMICAL LANDMARKING IN TOTAL KNEE ARTHROPLASTY PLANNING

Y. Roch¹³, D. Lozano³, N. Fougeron⁵, B. Gaulin¹², C. Horteur¹², Y. Payan¹, M. Bucki³, A. Perrier¹³⁴

¹ Univ. Grenoble Alpes, CNRS, UMR 5525, VetAgro Sup, Grenoble INP, TIMC, Grenoble, France ² Department of Orthopedics and Sport Surgery, CHU Grenoble Alpes, Échirolles, France ³ Twinsight, Grenoble, France ⁴ Department of Orthopedics and Traumatology, Groupe Hospitalier Diaconesses Croix Saint-Simon, Paris, France ⁵ Univ. Rennes, Inria, CNRS, IRISA-UMR 6074, Rennes, France

Contact: yse.roch@univ-grenoble-alpes.fr

Introduction

Total Knee Arthroplasty (TKA) is performed on over 100,000 patients annually in France, yet approximately 20% remain dissatisfied with functional outcomes [1, 2]. The recent paradigm shift toward personalized alignment strategies (kinematic, restricted kinematic, and functional alignment) has intensified reliance on CT-based morphofunctional metrics to guide implant positioning in all three planes [3, 4].

These metrics depend entirely on anatomical landmark identification, a process subject to inherent uncertainty due to definitional ambiguity, pathological remodeling, and algorithmic bias. While foundational sensitivity analyses have established key principles such as geometric amplification along short lever arms [5] and the primacy of reference frame landmarks [6], no framework quantifies individual landmark-axis contributions across the full metric spectrum nor translates these findings into differentiated acceptance criteria. This study aimed to establish an evidence-based hierarchy of critical landmarks by quantifying how positioning errors propagate into 14 key surgical metrics and to challenge the assumption that improved landmark accuracy translates directly into improved metric accuracy.

Methods

Monte Carlo sensitivity analysis (50,000 iterations per metric) was performed across 30 osteoarthritic patients (67.1 ± 8.8 years) undergoing TKA at CHU Grenoble Alpes. Preoperative full-leg CT scans were segmented using a validated deep learning pipeline (FDA 510k clearance K250290). Manual landmark annotations by two experienced orthopedic surgeons provided empirical positioning error distribution for 34 anatomical landmarks (repeatability: 1.83 mm; reproducibility: 2.34 mm). Atlas-based inverse morphing enabled cross-patient statistical aggregation. Two complementary sensitivity indices were computed: an amplitude-based index quantifying metric deviation per millimeter of landmark displacement (deg/mm; mm/mm) and the Chatterjee coefficient (ξ) capturing nonlinear statistical dependencies, including reference frame contamination effects (Fig. 1). The 90 % confidence interval width (CI₉₀) served as the primary sensitivity measure.

Results

Landmark and metric accuracy were systematically decoupled. Angular metric sensitivity spanned a 12-fold range (CI₉₀: $1.37^\circ \pm 0.22^\circ$ for mHKA to $16.87^\circ \pm 0.90^\circ$ for external tibial torsion) (Fig. 2). Two mechanistically distinct error propagation pathways were identified. First, geometric amplification: short transverse axes (60-80

mm) amplified in-plane positioning errors into large angular deviation, with malleolar landmarks reaching amplitude indices of 1.395 deg/mm for axial rotational metrics (Fig. 3) compared to 0.08 deg/mm for coronal metrics defined on 800-1000 mm spans. Second, reference frame contaminations: plane-defining landmarks exhibited elevated Chatterjee coefficients relative to their amplitude values. The lateral femoral condyle Y-axis, for instance, reached $\xi = 0.356$ despite an amplitude of only 0.053 deg/mm, reflecting simultaneous systematic bias propagation into multiple geometrically independent metrics (Fig. 1). A landmark achieving a 3.0 mm positioning error at the inferior medial femoral condyle can induce a mean 2.6° mechanical axis deviation and 1.8° joint line convergence error: clinically significant deviations that escape current detection protocols entirely.

Conclusion

Current validation frameworks applying uniform distance-to-reference thresholds across all landmarks are necessary but insufficient: they are blind to lever-arm amplification, reference frame contamination, and the differential downstream impact of positioning errors. Current regulatory submissions relying solely on landmark distance benchmarks fail to capture these mechanisms. Validation effort must be stratified by demonstrated metric-level impact: plan-defining landmarks require prioritized control regardless of individual amplitude values; high-impact endpoint landmarks warrant tolerances scaled to their quantified downstream effect; cross-metric consistency analysis is needed to detect reference frame distortions invisible to single-landmark inspection. As personalized TKA planning and digital twin-based surgical simulation increasingly depend on automated CT landmarking pipelines, the fragility of the measurement chain (from landmark to metric to implant positioning decision) must be characterized with the same rigor applied to implant performance itself.

References

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