AI-powered 3D Bone Reconstruction from X-Ray Imaging for Robotic Knee Arthroplasty

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INTRODUCTION: Total knee arthroplasty (TKA) is a standard intervention for end-stage osteoarthritis (>32M U.S. adults) [1]. Robotic-assisted TKA (RA-TKA) improves precision and reduces inter-surgeon variability, yet most systems rely on pre-operative CT for patient-specific registration - adding radiation, cost, and access barriers that exclude many patients [2, 3]. In contrast, X-Ray radiographs deliver far lower dose, are ubiquitous and reimbursed, but are inherently 2D and lack the 3D anatomy required for robotic planning [4, 5]. To address this, we developed an AI system that reconstructs patient-specific 3D femur and tibia from two orthogonal AP/LAT X-rays to replace CT in RA-TKA planning and registration. This study investigates whether AI-driven reconstructions from orthogonal X-rays can achieve registration accuracy comparable to CT-based models, a key requirement for safe and effective robotic-assisted TKA.

METHODS: We performed six (n=6) knee reconstructions using matched AP/LAT radiographs and corresponding CT-derived ground-truth meshes for training. A dual-encoder (AP/LAT) → fused-latent → 3D volumetric decoder network generated 256^3 voxel segmentations; training used CT-derived DRRs with combined Dice + surface-distance losses. Inference outputs were meshed via marching cubes. Accuracy was quantified after rigid ICP alignment to CT using surface error, volumetric overlap (Dice), and landmark/axis agreement (mechanical axis, TEA, PCA, tibial slope). We also simulated intraoperative paired-point + surface registration using the AI models versus CT, comparing translational and rotational errors and resection-plane deviations. No live human/animal procedures were performed; imaging data were de-identified.

RESULTS: Across six reconstructions, the AI system achieved a mean femoral surface RMS error of 0.72 ± 0.18 mm and tibial RMS error of 0.81 ± 0.22 mm. Representative AI-powered X-Ray 3D reconstruction RMS errors compared to CT ground truth are shown in Figure 1. Volumetric overlap reached Dice scores of 0.94 ± 0.02 (femur) and 0.92 ± 0.03 (tibia). Axis alignment showed mechanical axis deviation of 0.4° ± 0.2°, posterior condylar axis 0.5° ± 0.3°, and tibial slope error 0.6° ± 0.3. Variability between specimens was low, suggesting consistent reconstruction performance (see Table 1). Literature-reported thresholds for clinical acceptability in robotic TKA (CT-based) are within ~1 mm and 1°, placing our AI-based reconstructions within clinically viable limits [6].

DISCUSSION: Accurately replicating patient-specific 3D knee anatomy is essential for ensuring precise registration and alignment in robotic-assisted TKA. Reconstructions that deviate beyond 1 mm or 1° may compromise surgical accuracy, potentially affecting implant positioning and long-term outcomes. In this study, we evaluated the accuracy of an AI-based reconstruction system using standard AP and lateral radiographs. Six reconstructions were performed, and results showed mean femoral and tibial surface errors under 1 mm, with Dice overlaps above 0.90. Alignment analysis demonstrated deviations within 1° for mechanical axis, posterior condylar axis, and tibial slope, meeting commonly reported clinical thresholds. These findings suggest that X-ray driven AI reconstructions can achieve clinically viable accuracy for robotic surgical workflows. Moreover, currently we have access to over 100 additional paired CT and X-ray datasets that will be used to further train the system and reduce reconstruction errors. It is also important to note that all reported errors are benchmarked against CT-derived models, which themselves differ from true bone geometry; therefore, cadaveric testing remains essential to confirm reproducibility under surgical conditions and to establish total error calculations.

SIGNIFICANCE/CLINICAL RELEVANCE: AI-based 3D reconstruction from routine X-rays demonstrates sub-millimeter and sub-degree accuracy compared to CT, positioning it as a promising alternative for patient-specific registration in robotic TKA. This approach could reduce radiation exposure, lower procedural costs, and expand access to high precision robotic surgery. With further training on a larger paired CT–X-ray dataset and cadaveric validation, this system has the potential to provide a clinically viable pathway for replacing CT in preoperative workflows, ultimately improving precision, scalability, and patient safety in different types of robotic joint arthroplasties.

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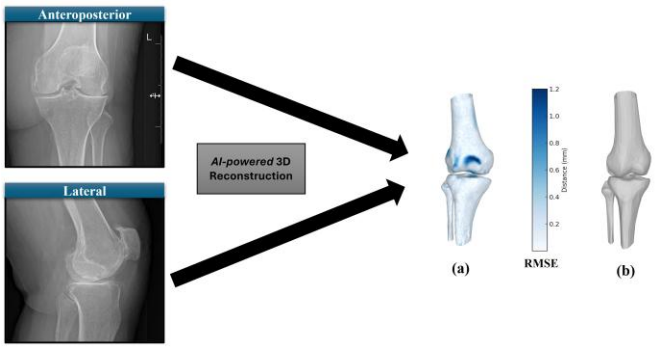

Figure 1. Knee surface distance map between (a) reconstructed 3D model and (b) ground truth CT model

Table 1. Quantitative Accuracy of AI-Driven 3D Reconstructions Compared to CT Ground Truth

Patient No.	Femur RMS (mm)	Tibia RMS (mm)	Dice (Femur)	Dice (Tibia)	Mech. Axis Error (°)	PCA Error (°)	Tibial Slope Error (°)
1	0.65	0.66	0.95	0.91	0.6	0.7	0.9
2	1.03	1.08	0.92	0.89	0.2	0.3	0.4
3	0.59	0.49	0.96	0.94	0.5	0.4	0.7
4	0.83	0.91	0.93	0.92	0.3	0.5	0.5
5	0.70	0.76	0.95	0.93	0.4	0.6	0.6
6	0.52	0.96	0.94	0.91	0.4	0.3	0.6
Mean ± SD	**0.72 ± 0.18**	**0.81 ± 0.22**	**0.94 ± 0.02**	**0.92 ± 0.03**	**0.4 ± 0.2**	**0.5 ± 0.3**	**0.6 ± 0.3**